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RENEWABLE ENERGY SYSTEM DESIGN:

A GUIDE TO

THE APPLICATION OF PHOTOVOLTAIC, WIND, AND MICRO-HYDRO POWER

A thesis

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PREFACE

I gratefully acknowledge the following, who have all contributed to the completion of this thesis:

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My parents, who convinced me (after much effort) of the value of education, and instilled in me a desire for learning.

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Finally I wish to acknowledge my Creator and my God.

"You alone are the LORD.
You made the heavens, even the highest heavens,
and all their starry host,
the earth and all that is on it,
the seas and all that is in them.
You give life to everything,
and the multitudes of heaven
worship you." (Nehemiah 9:6)

ABSTRACT

The primary objective of this study was to produce a guide for the application of photovoltaic, wind, and micro-hydro power to remote areas. The applications considered are those of generating electricity, and pumping water. An extensive literature review introduces and covers the main design considerations for each energy form. The primary decision-making areas are then examined, beginning with a look at the theory of electricity, and going on to discuss generators, inverters, energy storage, and mechanical transmission. Next, the assessment of the demand over a given time interval is considered.

The key questions of, "How big a system is required?", and, "How much energy will be produced?", are addressed for each energy form, along with various design considerations. For each of the energy forms the issue of quantifying the resource is examined in detail. The factors influencing the amount of power available are presented for each. This process of quantifying the power available is essential in order to be able to choose the optimum type of renewable energy to use for a given application in a specified location. Dealing with them together in one document allows the different energy forms to be assessed side by side, and a preliminary decision on the most promising type made.

For both wind and photovoltaic energy a computer model was created, drawing on available theory, in order to generate charts to assist in the design process. The photovoltaic design charts enable sunshine hour data to be converted to radiation in Kwh/m^2, and radiation on a horizontal plane to be converted to that received on a plane inclined at a specified angle. Other charts were produced which enable the most cost effective combination of array and battery to be selected for a given situation. The wind charts specify the amount of power which can be produced from a wind turbine with given characteristics operating in a specified wind regime.

The photovoltaic and wind design charts produced by the models enable the size of the relevant system required to be determined for a given situation. This information then allows a costing to be done to determine the cost of generating energy with a particular method. The procedure for evaluating and determining the true cost of the energy produced, based on life cycle costing, is then examined. This can then be used to assess the most economical means of meeting any particular demand.

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SYMBOLS AND ABBREVIATIONS

ENERGY

A	amps
A.h	ampere-hours
AC	alternating current
DC	direct current
e	efficiency of the transformer
emf	electromotive force
hp	horsepower
Hz	hertz
I_p	primary current
I_s	secondary current
kW	kilowatt
l	litres
m	metres
N	newtons
N_p	primary turns
N_s	secondary turns
PF	power factor
rpm	revolutions per minute
S	speed of rotation
T	torque
V	voltage
V_p	primary voltage
V_s	secondary voltage

PHOTOVOLTAICS

δ	declination
η	system efficiency
η_b	overall battery efficiency
ρ	ground reflection coefficient (ground albedo)
ϕ	latitude in degrees
C	days of load

DI	estimated daily demand for the month
DOD	maximum permissible depth of battery discharge
G_{sc}	solar constant equal to 1371 W/m^2
h	height above sea level in km
H	global radiation on a horizontal surface
H_b	beam radiation on an inclined surface
Hc	H calculated using equations
$H_{c(adj)}$	H adjusted by the regional coefficients
H_d	diffuse radiation incident on a horizontal surface
H_o	extraterrestrial radiation on a horizontal surface
H_r	ground reflected radiation on an inclined surface
H_s	sky diffuse radiation on an inclined surface
H_T	total global amount of radiation on an inclined surface
I	average H for the month
K	clearness index
Kt	monthly average clearness index
LOLP	loss of load probability
M	balancing parameter between the array and the battery
MPE	mean percentage error
n	Julian day of the year
NSR	no sun ratio ie. the ratio of the night load to the total daily load
R	ratio of the standard deviation in daily radiation over the average daily radiation
R_b	ratio of extraterrestrial radiation on an inclined surface to that on a horizontal surface
S	standard deviation of the radiation over a period of a month
$\underline{or}$	monthly average daily sunshine duration
S_o	monthly maximum possible daily sunshine duration
W	watts
W_s	sunset hour angle for a horizontal plane
W_s^1	sunset hour angle for the tilted surface for the average day of the month

WIND

A	area covered by wind pump rotor
C	Weibull scale factor
EPF	energy pattern factor
f	frequency
F	factor for extrapolating wind data

H	total pumping head
hp	horsepower
K	wind shape factor
kWh	kilowatt hour
m	metres
m/s	metres per second
mm	millimetres
n	total number of observations
SC	required storage capacity
V	voltage
or	wind velocity
v_1	velocity at height z_1
v_2	wind velocity at height z_2
w.h	watt hour
x	constant determined by the surface roughness

MICRO-HYDRO

α	angle of entry
θ	subtended angle
ρ	blade radius of curvature
ω	blade orientation of crossflow turbine
d	jet diameter in metres
D	discharge flange diameter of the pump operating as a turbine
d	impeller diameter of pump operating as turbine
f	output frequency (Hz)
H	available head (m)
H_t	total head measured to the bottom of the runner
Hz	hertz
K	empirically derived constant to calculate required pump size when operating as turbine
l/s	litres per second
L	nozzle width of crossflow turbine
m/s	metres per second
N	speed at which the pump should operate as a turbine (rpm)
n	speed in rpm
or	number of poles
N_j	number of jets

n_s	specific speed per jet
n_w	specific speed of the wheel
N_s	specific speed of the pump
P	power output of the turbine
Q	flow
q	flow
r1	runner radius of crossflow turbine
r_2	blade depth of crossflow turbine
t	blade spacing of crossflow turbine
U	velocity of the buckets
v	jet velocity in m/s
V_1	velocity of the jet
Z	empirically derived constant to calculate required pump speed when operating as turbine

FINANCE

AC	annualised cost of the photovoltaic array
BC	annualised cost of the battery storage unit
i	discount rate
m	number of years from the present to year n
n	expected system life

CHAPTER 1

INTRODUCTION

1.1 Problems with Conventional Power Generation

Twentieth century living demands large quantities of energy, particularly electricity. There are however problems associated with conventional methods of electricity generation. Large scale hydro power installations often demand that a lot of land is submerged by the dam, displacing both people and wildlife. Nuclear fission power remains unpopular because of the difficulties in the disposal of the radioactive byproducts, and the risk of accidents such as that which occurred at Cheronabyl. Escalating environmental problems such as global warming, the thinning of the ozone layer, acid rain, and smog, have caused many concerns about the sustainability and wisdom of the continued high use of hydrocarbon fuels such as oil, coal and gas to generate electricity.

Renewable energy, while not yet in a position to solve the world's energy problems, does offer to provide a valuable supplement to the world's electricity supply in the short term, and a major contribution in the medium to long term. The immediate growth area is expected to be the small scale remote area power user. Increasingly however, renewable energy is even used for feeding into the national grid. Within 30 years wind power alone could supply 25% of all of America's electricity needs (Thompson, 1992). The technology associated with renewable energies, particularly solar and wind power, has developed considerably in recent times. It is now just as reliable as mains supply if designed properly. Countries are eager to be less dependent on imported oil, so that they are less vulnerable to the impact of affairs in the volatile Middle East. Similarly, many individuals are looking to have a greater degree of autonomy from the state for their energy supply. The general development of the 'Green movement' has also meant more people are seeking an alternative and self sufficient lifestyle.

1.2 The New Zealand Situation

Within New Zealand as with many other countries there is a move towards a 'user pays' philosophy. Many sites in New Zealand are too far removed from grid power lines to be supplied with power at economic rates. Not only is it expensive to install power lines in the first place, but there are also on-going repairs and maintenance costs. Many lines in New Zealand are coming up for replacement over the next five years. The rebuilding of these lines has been estimated as costing up to $20,000 (Remote power systems, 1989).

Because of the deregulation of the electricity industry, people in remote areas connected by old lines face an uncertain future with regard to electricity pricing. Currently the Rural Energy Reticulation Council (RERC) continues to provide subsidies to local supply authorities to provide electricity to remote areas. Once the Electrical Supply Authorities have been corporatised however, the RERC is likely to discontinue these subsidies[1].

New Zealand is blessed with abundant wind and micro-hydro resources as well as having many locations with high levels of sunshine. These factors strongly favour the use of renewable energy in New Zealand.

1.3 Developing Country Application

Renewable energies offer the ability to pump clean water and to irrigate. These factors in turn provide the prospect of improved health and better nutrition. Where energy can be provided in the form of electricity or shaft power, jobs and industry, the basis of development, have a better chance of evolving.

1.4 Price of Renewable Energies

Prices of renewable energy systems have been steadily tracking downwards. Wind turbines operating in California are currently producing energy at US7 cents per kWh, while the new generation turbines will bring that down to 5 cents by 1995 (Thompson, 1992). The current price

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[1] Personal communication: Farley, Secretary of the Rural Energy Reticulation ouncil, June 1991.

of electricity in New Zealand at the time of writing is NZ9 cents per kWh for general home use and NZ5.1 cents per kWh for controlled storage and water heating. Prices of photovoltaic cells today at about US$5 per peak watt are about a quarter of what they were merely 10 years ago and they continue to fall. Traditionally economic analysis has ignored environmental impact yet when this is considered renewable energies become even more attractive.

Within this thesis the three forms of energy examined are photovoltaic (the generation of electricity using solar cells), wind, and micro-hydro power. These three were selected as they were thought to have the most potential for power generation in remote areas. While there is a lot of literature regarding their use, most of it is time consuming and difficult to work through for the lay person who is interested in the application of these forms of energy. Given the increasing popularity of renewables, and the scarcity of readily accessible and understandable information, it was considered that a publication examining the design considerations of the design renewable energy systems would be welcomed.

The objectives of this study are given in chapter 3.

CHAPTER 2

LITERATURE REVIEW

2.1 Overall Introduction to Literature Review

This literature review provides an overview and introduction to the application and theory of photovoltaic, wind and micro-hydro power. Where references are used extensively within the body of the thesis they may only be referred to here in a brief manner. Aspects of the subject area which influence the determination of key design issues, such as the wind turbine or photovoltaic array sizing, are generally dealt with within the chapter concerned, although may be briefly touched on within the literature review.

SOLAR ENERGY
Literature Review

2.2 Introduction

There is a large variation in the uses to which solar energy can be put, from direct crop drying to very sophisticated systems required for space satellites (Groumpos & Papageorgiou, 1987). It was in 1958 that solar cells were first used as a power source in space and this continued to be their main area of application up until 1973 (McCarthy & Wrixon, 1988).

There are two forms of sunlight conversion which result usable energy. One is thermal and the other is electrical. Of the two, electrical is the more promising and versatile (Groumpos & Papageorgiou, 1987). Thermal sunlight energy conversion is however much more efficient and ideal for water heating applications. In this thesis it is predominantly the photovoltaic conversion of sunlight to electricity which is considered.

2.3 General Comment on References

Intermediate Technology Publications[2] publish several excellent books in the photovoltaic as well as other renewable energy subject areas. Two which are particularly relevant to photovoltaics are by Kenna and Gillett (1985) and Derrick et al (1991).

Western (1990) provided very interesting information about the assessment of solar radiation and the clearness index in New Zealand. Gopinathon (1990) examined the accuracy of the Lui and Jordan, and Hay models for predicting the radiation received on an inclined slope. This was then compared to actual measured data. In so doing he provided a useful summary of the two types of models. Charters (1986) presented an excellent overview of both solar and wind power, examining also the electrical side of the design.

The photovoltaic effect may be described as 'the generation of an electromotive force as a result of the absorption of ionizing radiation'. Solar cells use the photovoltaic effect to generate a voltage and a direct current. Duffie and Beckman (1980) made an outstanding contribution to understanding in the area of solar engineering with their book which covered heat transfer, radiation characteristics, solar collectors, concentrators, energy storage, solar water heating, solar heating systems and solar cooling. It also contained background theory to the understanding of the assessment of radiation on a horizontal and inclined plane.

2.4 Design Overview

Photovoltaic energy is often a suitable source of power for limited electricity needs but becomes uneconomic as the demand increases. De Gromard and Cornut (1986) stated that for many situations where the power requirement is below 1 Kwh/day, photovoltaic energy is the most economic.

Stand Alone Photovoltaic Systems (SAPV) have several significant components. The most important is the solar array. This is comprised of weather proof modules made up of many solar

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[2] **Address:-**

Intermediate Technology Publications Ltd
103 - 104 Southhampton Row
London WC1B 4HH
UK.

cells all connected together in series and parallel configurations (Groumpos & Papageorgiou, 1987), to achieve the desired voltage and current.

Key factors to consider in the design of photovoltaic systems are: energy yield, power level required, reliability, maintainability, repairability, cost and the system's expected life. To achieve a robust and reliable system careful attention must be paid to the selection of all the components of the system (Hertlein, 1986). Good design of photovoltaic systems results in substantial cost savings.

2.5 Sizing Photovoltaic Array

It has only been in the last five years that the sizing of the various elements of a SAPV was done in anything other than a trial and error fashion. Khouzam, Khouzam and Groumpos (1991) discussed array sizing. They presented a method to determine the array parameters that are required to supply varying loads. They follow on from earlier work which Khouzam (1990) did in the same field.

Groumpos and Papageorgiou (1987) wrote a very useful article in which they described an algorithm for the sizing of the solar array and battery capacity of a SAPV. They proposed a formula for determining the array area. A 'M' factor was used in the sizing of the solar array and the battery as a balancing parameter for different cost ratios of array to battery. This method is used within section 6.15.4.

Chapman (1989) presented the array size as a function of the array tilt angle, the average horizontal insolation and the latitude of the site. McNelis (1986) gave a nomogram for the approximation of sizing of a photovoltaic pumping system ie. solar array size versus capacity. Saied and Jaboori (1989) provided a method for determining the total number of cells required from the rated output power and the voltage and current characteristics of a single solar cell. They also gave an optimisation technique by which it is possible to determine the array configuration. Optimal motor voltage and current ratings as well as the motor field parameter, which yields the maximum amount of mechanical energy, can then be determined for given radiation and ambient temperature variation curves.

2.6 Determining Storage Requirement

2.6.1 Battery Storage

The output of a solar panel is well suited to battery charging as it is the current rather than the voltage which varies with radiation intensity (Charters, 1986). Storage is required to enable the load to be satisfied when there is insufficient radiation or no radiation.

To determine the amount of battery storage required the variability in radiation must first be quantified and from there the designer must select a combination of array size and storage capacity that will satisfy the load the required percentage of the time (Chapman, 1989). This is termed the 'confidence level' and is represented mathematically by the loss of load probability (LOLP) which describes how often the photovoltaic-storage system will be unable to meet the load requirements. An LOLP of 1 means that the load will never be satisfied while a LOLP of 0 means that it will always be satisfied. To determine the long term LOLP and its distribution, data on radiation and demand profiles are required.

Chapman (1989) has generated sizing nomograms showing the required storage capacity as a function of the LOLP. Nomograms are also given which define a curve of array size versus storage capacity, from which a designer is able to determine equivalent array-storage size combinations. Khouzam, Khouzam and Groupmpos (1991) provided a means to determine battery parameters as did Khouzam (1990).

Battery overcharging is often a problem with photovoltaic systems. If nothing is done to correct this it will significantly reduce the life of the battery.

2.6.2 Hydro Storage

This form of storage is one of the most simple means of storing energy. It is however only suitable where there is an ample supply of water available and where there is topography for dam construction. Dunn (1986) devoted a chapter to energy storage, examining both battery and micro-hydro storage.

2.7 DC and AC

Most DC power systems use a voltage regulator to protect the battery and the load appliance from excessive voltage. This regulator, connected between the battery and the array, dissipates any excess energy when the battery bank is fully charged. A DC circuit also needs to have a 'blocking diode' between the array and the battery. This prevents the current flowing from the battery to the array during the night. To produce AC power from a DC solar cell an inverter must be placed in the circuit before the load. Inverters should be carefully chosen to closely match the power demand of the load (Charters, 1986).

2.8 Matching Load to Array

The quality of load matching to the solar cells has been defined by Appelbaum (1987), as the ratio of the load input power to the maximum available power of the photovoltaic generator for a given level of radiation.

Optimum load matching is desirable because it means that the size of the photovoltaic array (and therefore its cost) can be minimised. The quality of load matching depends on the photovoltaic array characteristics, the load characteristics and the radiation profile. In a well matched load the amount of electrical energy supplied to the load is close to the maximum array energy (Khouzam et al, 1991). Optimum matching can be achieved by selecting the array maximum power point parameters with respect to the load rated parameters.

Khouzam (1990) introduced 'the load matching factor' as defined by the ratio of the load energy to the array maximum energy in a one day period. This is effectively the same measurement as discussed by Appelbaum (1987). Khouzam went on to use this as a criteria for determining the quality of load matching. The more closely the load can be estimated the better because a closer match is then able to be obtained. With photovoltaics it is normally possible to have a very good match to a battery as long as the correct number of cells are chosen and the circuit voltage drops are taken into account.

2.9 Tracking Arrays

Using a tracking array can result in 33% more energy being produced throughout the course of a year compared to a fixed array (Baltas et al, 1986). These do, however, make the system significantly more complex and expensive.

2.10 Load Control

System controls are very important. This includes protection against excess voltage (Groumpos & Papageorgiou, 1987). Some form of load control also needs to be incorporated into the photovoltaic system to minimise the need for storage and to increase the system's reliability.

A load control unit can increase the amount of energy available by connecting to different electrical loads whenever excess energy is generated, such as during periods of high winds. Where battery storage is used a relay can be used which is set to close its contacts when the voltage exceeds a preset limit. Marier (1981) described a system where an electronic circuit transfers charging to the auxiliary power generator when the batteries need to be charged and there is no wind. If the batteries are fully charged and there is excess energy being generated, the load control switch connects the battery bank to another load such as a water heater.

2.10.1 Lightning Protection

Published experiences with the different lightning protection systems are still insufficient and contradictory (Traeder, 1986).

McCarthy and Wrixon (1988) described two different types of lightning protection used on a particular site. One involved the use of lightning rods to protect the building and steel work and the other uses a varistor and spark gap combination in the junction boxes to protect the electrical equipment.

2.11 Photovoltaic Water Pumping

The suitability of photovoltaics for pumping water is well established (Pulfrey et al, 1987). It has been described as being one of the most viable photovoltaic applications (Baltas et al, 1986). In 1983 only 400 solar pumps had been installed worldwide. This figure rose dramatically to more than 3,000 in 1986 (McNelis, 1986).

Photovoltaic systems are now available at prices competitive with diesel for a wide range of small scale irrigation and water supply applications. Reliable solar and water resource data must be obtained for a proper design. Accurate information on the depth of the water table and its seasonal variations is particularly important (McNelis, 1986).

2.11.1 Photovoltaic Pumping Design Overview

Photovoltaic pumping systems may be relatively simple comprising of little more than a photovoltaic array, a DC electric motor coupled to a water pump, and pipe work from the source to the delivery point. Batteries can usually be avoided since reservoir storage is cheaper and easier to maintain.

An overall systems approach has to be followed for the design of a photovoltaic water pumping system (Baltas et al,1986). Overall daily output must be maximised for a given solar input. The characteristics of all the components, including the suction and delivery pipe work, need to be matched to achieve the most cost effective solution.

With the case of photovoltaic pumps the electrical load must be such that its current-voltage characteristics curve intercepts that of the photovoltaic generator as closely as possible (Lasnier et al, 1987).

2.11.2 Types of Pumps

McNelis (1986) described the following as the four main types of pumps in use in conjunction with photovoltaic systems:

1. submerged motor and pump units often consisting of several impellers,
2. submerged centrifugal pumps driven by a shaft mounted at ground level,
3. submerged reciprocating positive displacement pumps,
4. floating motor and pump units with a self priming tank.

2.11.3 Motor Selection

Permanent DC motors are normally regarded as being the most suitable for use in photovoltaic systems where no battery storage is used. The reason for this is that they are reliable, have a reasonably low cost and can operate over a wide range of input voltages (Pulfrey et al, 1987). DC motors may, however, be more than twice as expensive as AC motors, although this is partly offset by the cost of the inverter required for an AC motor (McNelis, 1986).

Saied and Jaboori (1989) presented a procedure for the design of systems where DC motors are supplied directly by photovoltaic solar generators. They examined the use of solar energy after its conversion in a photovoltaic solar array to supply DC motors used to operate pumping loads. They described the following factors affecting the matching condition:

1. the strongly non linear and radiation dependent voltage current characteristics of the solar cell,
2. the array configuration, that is the number of cells in series and strings in parallel,
3. the type of mechanical load,
4. the type of DC motor used,
5. the cell thermal conditions, particularly changes in the ambient temperature.

One procedure described for matching was to introduce a power control or conditioning unit, such as a DC transformer, between the solar array and the DC motor. In some cases an AC motor with an AC-DC converter may be the more appropriate option.

Near perfect matching is important as it results in the maximum amount of mechanical energy being available to the pump (Saied & Jaboori, 1989). It is relatively simple to match a motor to a pump as regards torque and speed. It is however another matter when it comes to matching a photovoltaic array to a motor used for near fixed head pumping (Pulfrey et al, 1987). A relatively new type of pump uses a brushless DC motor called an electronic switch motor. This motor accounted for the very high efficiency of the pump of over 90% in the research described by Waterbury (1990).

2.11.4 Pump Output

Of the many different ways of defining the rating of a photovoltaic pump, two of the most common are peak photovoltaic array power and peak hydraulic power. Because the average volume of water delivered over time is of primary interest to end users, the preferred means of referring to pump capacity is to speak of the daily volume of water delivered at the design head and at the design daily solar radiation level (McNelis, 1986).

McNelis (1986) provided a graph which showed the capacity range of a selection of 'off the shelf' photovoltaic pumps. This is seen to vary from 1 to 250 m^3 and from 1 to 100 m head.

The pump described by Waterbury (1990) which employs a brushless DC motor, can be configured to operate within a range of 28,300 litres (1,000 cubic feet) of water per day from a depth of 10.6 metres (33 feet) to 6,800 litres (240 cubic feet) per day from a depth of 40 metres (130 feet) when using the maximum of 14 panels each approximately 0.45 square metres. Even when using four such panels the pump delivered 9,912 litres (350 cubic feet) of water per day from a depth of 10 metres (Waterbury, 1990).

Fraidenrach and Costa (1988) described a procedure for calculating the mechanical energy available for water pumping, E_m, as follows:

$$E_m = H_c A_p f_c \phi \tag{2.1}$$

where:

H_c is the daily collected energy averaged over a month

A_p is the area of the photovoltaic system

F_c is the overall conversion efficiency

ϕ is the 'utilisability' factor

The authors went on in the same article to give a formula which can be rearranged to calculate the volume of water pumped per day, V_b, in the following way:

$$V_b = \frac{3E_m}{2\Delta P_M + \rho g H} \tag{2.2}$$

where:

ΔP_M is the maximum pressure difference

H is the level difference

The maximum pressure difference is calculated by adding together all of the pressure losses throughout the whole of the hydraulic network, to the level difference, H.

2.11.5 Reliability

McNelis (1986) examined issues of reliability associated with photovoltaic pumping systems. One factor contributing significantly to the marked increase in reliability of photovoltaic pumps has been the change from systems with surface mounted motors and submersed pumps to that of DC and AC submersible pump motor sets. Shaft and head bearing maintenance was also often a problem, while problems with the photovoltaic array itself was rare.

Early problems McNelis (1986) experienced with electronics associated with brushless DC motors were overcome while the problem of pumps running dry still occurred occasionally. Even where systems have been fitted with over speed protection or float switches these have sometimes failed with the result of the motor burning out. Proper consideration of the characteristics of the well or borehole would help to avoid these problems.

2.11.6 Electrical Array Reconfiguration Controller

Where the matching of a load to a photovoltaic generator is poor a maximum power point tracker, MPPT (also called an electrical array reconfiguration controller), should be included in the system. This is a device fitted to photovoltaic arrays to ensure that the maximum energy can be extracted from these cells. This is done by electrically manipulating the voltage and current output (Charters, 1986).

An article by Appelbaum (1988) would assist a designer in deciding whether or not to include a MPPT in any given system. He suggested that the decision process depends on the following factors: load type and profile, climatic conditions, the cost of the MPPT and its efficiency, and the gain in energy to be had from using one.

Salameh and Dagher (1990) presented a way to optimise the performance of photovoltaic powered water pumps by producing sufficient current to start the motor at relatively low irradiance levels. This meant that the pump could operate for more hours in a day. The method used screw type volumetric pumps which were direct coupled to a photovoltaic powered permanent magnet DC motor. This type of pump used has a constant starting torque independent of the speed.

The method described by Salameh and Dagher used an electrical array reconfiguration controller which was able to sense the level of radiation. This then selected the most appropriate current to voltage ratio for both starting and for steady state operation. This was achieved by altering the connection configurations of the photovoltaic panels to the motor (Salemah & Dagher, 1990).

2.11.7 Batteries

Baltas et al (1986) discussed how, by including a battery in the design, pumping hours could be extended. If the equivalent amount of water was pumped over a longer time period this resulted in a lower draw down and lower pipe friction losses (section 2.11.8 discusses this in more detail). For centrifugal pumps they argued that it could mean that more time was spent operating at the maximum efficiency point of the system. They noted that power losses due to charging and discharging would however degrade the efficiency of pumping.

Salem, Motawakel and Bassyouni (1989) described a design method for photovoltaic-battery storage systems under tropical conditions. The part of the paper specifically related to the tropics was for the calculation of the irradiation of tilted surfaces, while the rest was relevant for all photovoltaic storage applications. A graph was given which showed how the design radiation relates to the number of days storage for a given long term assurance factor (very similar to the LOLP).

Array area and rated capacity sizing diagrams were also given by Salem, Motawakel and Bassyouni. These can be used to calculate the capacity and area of the required photovoltaic system once the number of days storage, system efficiency and the daily load demand are known.

2.11.8 Well

The draw down of a well at various pumping rates is a very important factor in the design of a photovoltaic pumping system. Better performance may in some cases be able to be achieved by a more careful selection of the well screen, the right choice of drilling procedure, or even just cleaning of the existing well (Baltas et al, 1986). Baltas et al also examined the issue of pipe sizing with respect to photovoltaic systems.

It will be usually the dynamics of the well which determines whether or not some form of electrical storage system should be used. If the water level barely changes during pumping, using batteries is unlikely to be justified unless there is little or no ability to store water. When using batteries water can be pumped from a higher level in a well. The reason for this is because the pump is not restricted to operating only when the sun is out, pumping an equivalent amount of water will require a reduced pumping rate. A lower pumping rate in turn means that the well's draw down is less while the reduced flow rate means that friction losses are reduced.

2.12 Developing Country Applications

It has been estimated that less than 20% of the population of developing countries are supplied with electricity, while 75% of the population are in danger of becoming marginalised[3] in the long term (de Gromard & Cornut, 1986). The introduction of electric power at an affordable price may reduce this risk of marginalisation.

Photovoltaic systems are attractive for developing situations because of their inherently low maintenance requirements and because of particularly high levels of solar radiation often occurring in these countries. The use of photovoltaics in the third world is however still at an early stage (Hertlein, 1986). Hertlein (1986) reviewed the technology and design of photovoltaic systems relevant for use in developing countries.

2.12.1 Solar Pumping

Photovoltaic water pumping has a high growth potential in developing countries (Baltas et al, 1986). Part of the reason for this is that the cost of photovoltaic water pumping is steadily declining. Photovoltaic pumps are an increasingly viable option for village water supplies in remote parts of developing countries because no fuel is required and maintenance requirements are minimal.

An article by Pulfrey, Ward and Dunford (1987) examined a photovoltaic powered system designed for operation at heads around 35 m. They concluded that it is an excellent candidate for use in the supply of water to villages in many parts of the tropics. Medium head pumping is of particular interest in parts of the dry tropics where the water table often lies in the range of 15 to 50 m. Since 1979 the United Nations (UN) development programme has been funding a World Bank project testing and demonstrating small scale solar water pumps.

[3]regarded as insignificant; barely or unprovided for

WIND POWER
Literature Review

2.13 Introduction

The ancient Egyptians are thought to have used turbines as early as 3600 BC for irrigation and for grinding grain. Wind mills are reported to have been in use in China and Japan from 2000 BC. They were also used in Babylon for pumping water around 1700 BC (Golding, 1976). The horizontal axis turbine was developed in Europe in the 12th century and by the 13th century was very widely used for corn grinding and water pumping.

The turbine played a dominant role in opening up the midwest of the USA by supplying a source of power for irrigation and water supply (Dunn, 1986). The first generation of electricity from a turbine occurred in Denmark in 1890 (Dickenson & Cheremisinoff, 1980), while the most common application of wind mills throughout history has been for water pumping (Nahas et al, 1987).

A common problem with turbines has been that due to their relative immaturity many were not adequately designed and so failed in the field (National Research Council, 1977). However over the last five years, reliable and virtually maintenance free wind turbines have been produced (Fraenkel, 1990).

2.14 General Comment on References

Sources likely to be of most interest to people wanting to apply wind power, and the major sources used for this study are: Edwards (1986), which has been drawn on extensively by this author; Golding (1976), which is comprehensive and excellent albeit a little dated and technical in some areas; Wegley et al (1980) and Cherry's wind energy resource survey (1987), which are both extremely useful in the assessment of a potential wind site; and Lancashire et al (1987), which is an excellent reference for wind water pumping in a developing country application.

2.15 Wind Turbine Power Output

The amount of power possessed by wind is quite different to the amount of power that is able to be extracted. One reason for this is that at low wind speeds it is not worth running the turbine and so no energy is produced until the velocity of the wind reaches, what is termed, the cut-in wind speed. With most turbines once the rated wind speed has been reached no additional power is produced even if the wind speed increases beyond this point. If wind speed continues to increase to the point where it is necessary to shut the turbine down to avoid damage (the furling point) no further power will be extracted by the wind turbine.

Section 7.8 in this study examines the various types of wind turbines. An article by Ushiyama and Nagai (1988) showed the effect of seven design parameters on the aerodynamic performance of Savonius rotors. These are presented in section 7.8.2.

2.15.1 Determining the Theoretical Maximum Turbine Efficiency

Another reason for the difference in wind power, and the proportion able to be harvested, is that the theoretical maximum amount of power able to be extracted from a wind stream is 59.3%. This was calculated in 1927 by A. Betz and is therefore called the Betz limit. The basic procedure he went through was as follows:

The slowing of wind passing through a wind turbine occurs in two stages, one before and one after its passage through the rotor.

Therefore:

V_1 = wind speed at a considerable distance up wind
V = wind speed passing through the rotor
V_2 = wind speed at a considerable distance down wind from the rotor

If M is the mass of air passing through the rotor per unit time, the result of the change in momentum is M (V_1 - V2) which is equal to the resulting thrust. The power absorbed is therefore $\dot{M}$ (V_1 - V_2) V.

The rate of change of kinetic energy in the wind can be described by equation 2.3:

$$\frac{1}{2}M\ (V1^2 - V2^2) \qquad (2.3)$$

These two expressions are equal so:

$$M(V1 - V2)V = \frac{1}{2}M(V1^2 - V2^2) \qquad (2.4)$$

from which one can derive equation 2.5:

$$V = \frac{(V1 + V2)}{2} \tag{2.5}$$

Therefore slowing of the wind V_1 - V before the rotor is equal to the slowing V - V_2 behind it.

The power extracted by the rotor is:

$$P = \rho A V (V1 - V2) V \tag{2.6}$$

where ρ is the air density and A is the swept area of the rotor.

$$\begin{aligned} P &= \rho A V^2 (V_1 - V_2) = \rho A \left(\frac{V_1 + V_2}{2}\right)^2 (V_1 - V_2) \\ &= \rho \frac{A V_1^3}{4} [(1+\alpha)(1-\alpha^2)] \\ &\textit{where} \\ \alpha &= \frac{V_2}{V_1} \end{aligned} \tag{2.7}$$

It can then be shown that the power is a maximum when $\alpha = 1/3$. That is, when the final wind velocity V_2 is one third of the upwind velocity V1. Therefore the maximum power which can be extracted is described by equation 2.8:

$$\rho A V1^3 x \frac{8}{27} \tag{2.8}$$

Therefore an ideal wind turbine could then extract 16/27 (59.3%) of the power in the wind (Golding, 1976).

2.15.2 Turbine Operating Efficiency

In practice, because of losses in the rotor, transmission, and generator turbine, efficiency is generally in the range of 25 to 45% (Golding, 1976). Horizontal axis wind turbines tend to be up in the higher end of the range while vertical axis wind turbines are significantly less efficient (National Research Council, 1977). The operating efficiency of turbines is also influenced by their size with smaller turbines generally being less efficient.

2.16 Tip Speed Ratio

The tip speed ratio, (λ), can be defined as 'the ratio of the speed of the tip of the rotor blades to the speed of the wind stream'.

$$\lambda = \frac{\Omega R}{V_1} \tag{2.9}$$

where:
Ω is the angular velocity
R is the rotor radius
and V_1 is the undisturbed wind speed

Figure 2.1 illustrates the effect of tip speed ratio on efficiency, C_p, for different rotors. Edwards (1986) presented a similar graph. These graphs can be used to determine the optimum tip speed ratio for different rotors. In practice, the performance of a given wind turbine can be determined by examining the C_p versus lambda characteristics (Dunn, 1986).

By making an assumption that the efficiency is constant for all wind speeds between the cut-in and the rated wind speed, the estimation of annual energy can be based entirely on the power duration curve. This introduces some error but does not effect the energy estimation significantly (Golding, 1976). This has in fact been done in generation of design charts described in section 7.10.

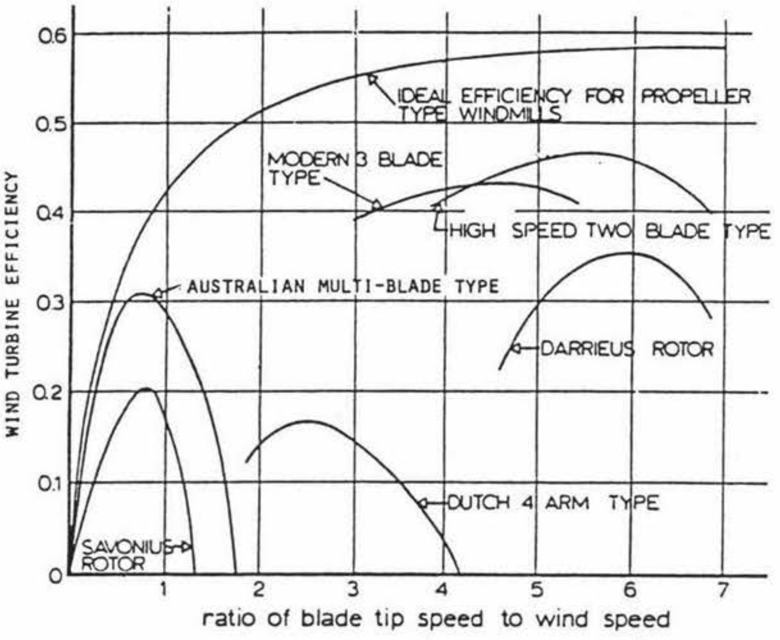


Figure 2.1 Efficiency versus Tip Speed Ratio (Dunn, 1986)

2.17 Drag and Lift

Wind turbines can be classified into drag and lift type turbines. Drag is the force on an airfoil or wind turbine blade which acts in the same direction as the wind flow. The drag force is usually expressed in terms of the dimensionless drag coefficient, C_D, as follows:

$$C_D = \frac{drag\ force}{1/2\rho v^2\ x\ area} \qquad (2.10)$$

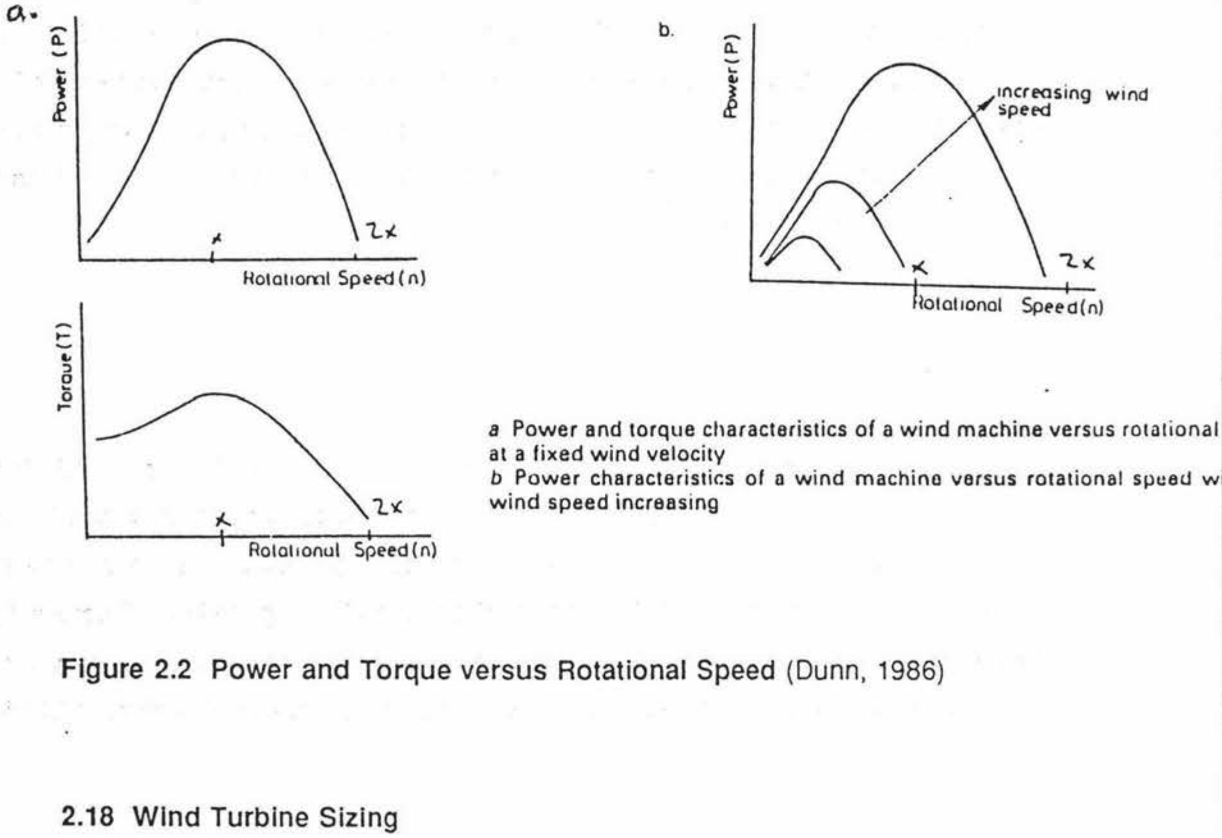
where V is the wind velocity and ρ is the fluid density (Dunn, 1986).

The lift type have blades which act in a similar manner to aircraft propellers. When a plate is placed at a small angle to the direction of an air flow then, in addition to the drag force, the plate will also experience a force at right angles to the flow. This is called the lift force . This is caused by a pressure differential between the upper and lower surfaces of the plate.

Lift can also be expressed in terms of a dimensionless number, the lift coefficient C_L, where:

$$C_L = \frac{lift\ force}{1/2 \rho \dot{v}^2\, x\, area} \tag{2.11}$$

C_L depends on the Reynolds number and the angle of attack (Dunn, 1986). Both types can be either horizontal or vertical axis turbines. Figure 2.2(a) below illustrates how power output and torque vary with rotation speed for a fixed wind velocity v_1. A different set of curves will be required for every different wind speed as shown by figure 2.2(b) (Dunn, 1986).



a Power and torque characteristics of a wind machine versus rotational at a fixed wind velocity
b Power characteristics of a wind machine versus rotational speed wi wind speed increasing

Figure 2.2 Power and Torque versus Rotational Speed (Dunn, 1986)

2.18 Wind Turbine Sizing

The correct sizing of a wind turbine is of critical importance. Designing of systems for the months with the highest demand may in some cases result in a system oversized for the bulk of the year (Todd, 1987). This is because of the variation in wind speeds.

2.19 Load Matching

Load matching is an important factor in determining how much power can be obtained from a wind turbine. Turbines and loads must be matched so that the load absorbs the maximum power available at the corresponding speed of rotation of the turbine. Matching pumps and generators to incompatible turbines results in poor power output. Pumps and generators are now available which have characteristics similar to those of turbines therefore making the matching job easier (Dunn, 1986).

2.20 Speed of Revolution

The standard method of operating medium and large turbines in recent years has been at a constant rate of revolutions (Wilmhurst, 1988). However where turbines are allowed to operate at a theoretically fixed tip speed ratio (and therefore a variable rotational speed), up to 50% more power is produced than from an equivalent turbine with a fixed speed. Variable speed rotational operation does however impose some design constraints on the manufacturer. This is largely due to the mismatch between the turbine rotor and the electrical generator torque and speed characteristics (Watson et al, 1983).

2.20.1 Gearing

If the turbine shaft speed is too high for a reciprocating pump a gearbox will be required (Dunn, 1986). In smaller turbines with propeller diameters of only two to three metres, gearing can usually be dispensed with because they can be designed for high rotational speeds. However gearing does become necessary with larger rotor diameters (Golding, 1976). Before a final decision on the gearbox ratio can be made, the starting behaviour, the stability in the working points, and the degree of overloading of the system should be assessed (Goezinne & Eilering, 1984).

2.21 Storage

Small wind and photovoltaic systems almost always require some form of energy storage, usually in the form of lead-acid batteries (Todd, 1987). An advantage of a wind turbine is that it is able to give equalising boost charges to battery banks rather than just shallow cycling such as received from solar photovoltaic panels. Surplus energy can then be used to heat water or whatever use is desired (Watson et al, 1983). Ramakumar (1983) outlined the various forms of energy storage options for wind energy systems as follows: mechanical; water pumping;

pneumatic; flywheels; chemical; thermal; and electric.

2.22 Power Shedding

When there is excess wind power and the storage facility is full then the wind power must be shed in some way. There are three main ways this is done:

1. dumping the load,
2. permitting over speed and activate a passive pitch control mechanism,
3. having a rapid action pitch control on the wind turbine.

Lipman (1988) examined the advantages and disadvantages associated with these options.

2.23 Control and Regulation

A control device is required on wind turbine systems incorporating battery storage to prevent under and over charging which might otherwise cause premature battery failure (Todd, 1987). Todd went on to examine other functions a control device might be required to perform.

2.24 Protection Against Strong Wind

It is important that adequate attention is paid to the braking system of a wind turbine (Cromack & Oscar, 1984). All the modern turbines, with the exception of some of the smallest ones, have some form of over speed control. Often it involves the turning of the rotor's edge to the air stream. 500 W to 2,000 W units often employ tilt back mechanisms (Watson et al, 1983).

Golding (1976) presented other ways of braking or controlling the speed of wind turbines as follows:

1. Varying the blade pitch so surplus power is spilled over the side of the rotor. This can be triggered by the centrifugal force on the blades as the rotational speed increases above a set level. The blade fixing at the hub may have a spiral socket so the blade changes pitch as it is pulled out radially by the centrifugal force. Alternatively, the blade spindle may be bent near the hub so the centre of gravity of the hub lies off the axis of

rotation.

2. Mounting the rotor off centre from the axis of the supporting pole so that it turns out of the wind at high wind speeds.
3. Using auxiliary air-brake vanes rotating with the rotor but rotating on separate arms. These are held in by springs and fly outwards, producing a braking effect, when the rotational speed rises above a given value.
4. With more traditional sail type turbines, sails can be made of a number of hinged shutters which allow strong winds to pass through.

2.24.1 Brakes

In developing countries wind turbines are often protected from high winds by using a manually controlled brake. This suffers from the disadvantage of requiring almost constant attention, allows no output in high wind speeds, and is not failsafe (Goezinne & Eilering, 1984).

2.25 Maintenance

Some turbines are now available which require virtually no maintenance. It may however be preferable to maintain a low maintenance requirement, such as the greasing of bearings, because this then allows a close up visual inspection (Watson et al, 1983).

2.26 Methods of Orientation

It is only the horizontal axis wind turbines that require some method of orientating the rotor to the wind. Vertical axis wind turbines such as the Savonius and the Darrius do not require any orientation.

The most common ways of orientating horizontal axis wind turbines are using:

1. a tail vane,
2. a secondary rotor,
3. downstream mounting,
4. a servo motor.

(Dunn, 1986)

2.27 Electricity Generation

For successful design, particular attention must be given to the alternator or generator (Watson et al, 1983).

Use of an induction generator, or an alternator (which runs at a constant rate of revolutions), means that the rotor is required to also run at a constant rate of revolutions instead of the constant tip-speed ratio (Golding, 1976). An advantage of DC generators is that a variable speed of rotation is practical. DC generators and accumulators are therefore commonly used instead of alternators. There is a maximum size generator for any given rotor size beyond which there is no advantage in terms of energy production (Cromack & Oscar, 1984).

Cromack and Oscar (1984) examined the selection of the most appropriate generator for any given rotor under specified wind conditions. This is shown to be dependent on whether or not the turbine is running at a constant rotational speed and the particular cost function used. Lipman (1988) examined the advantages and disadvantages of synchronous versus induction generators when associated with wind-diesel systems. Where power is generated using a generator the voltage is usually low. This fact, combined with the low power capacity means that generators must be located near their load. This results in a much reduced flexibility in terms of a choice of site (Golding, 1976).

Where a wind generator is used in combination with battery storage, a rectifier needs to be used to convert AC to DC. An inverter and transformer will also be needed to convert the DC from the batteries back to AC for appliance use (Charters, 1986).

2.27.1 Electrical Array Reconfiguration Controllers

Matching is in some cases able to be improved by changing the voltage and current levels between the source and the battery by a certain ratio. This ration is determined by operating conditions using an electrical array reconfiguration controller (section 2.11.6 examined the use of these in combination with photovoltaic systems). Electrical array reconfiguration controllers can be used to reduce wind generator cut-in speeds and to improve high wind speed output (Todd, 1987).

2.28 Wind Water Pumping

To design an optimum wind water pumping system for a particular site it is necessary to know the depth of the water table, its seasonal variations, and the flow characteristics of the source (Batchelor & Dunn, 1986).

2.28.1 Types of Pumps

The traditional method of wind water pumping has been to use a mechanically coupled double acting piston pump or an electrically coupled centrifugal pump.

Piston Pumps

Gasch et al (1987) discussed wind pumping using piston pumps. The power requirement of a piston pump is shown to be lineally dependent on the number of revolutions, n, the working volume, V, and the total head, H:

$$P_{mech} = \frac{\rho_w g\, H\, V n}{\eta_{mech}} \tag{2.12}$$

where η_{mech} is the mechanical efficiency and ρ is the density of water.

If the graph of the power requirement of the piston pump is then superimposed on the characteristic of the wind turbine, the intersection point gives the rotational frequency dependent on the wind speed, n = n (v), the ideal hydraulic pump output:

$$P_{hybrid} = \rho_w g H V n(v) \tag{2.13}$$

The hydraulic pump output:

$$P_{hydr} = \rho_w g Q H \tag{2.14}$$

and the characteristic line of delivery:

$$Q(v) = Vn(v)/\eta_{vol} \tag{2.15}$$

The total efficiency of the system can be obtained from the product of the individual efficiencies or from the relationship between pump output and theoretical wind power.

$$\eta_{WPS} = P_{hydr}(v)/(\frac{1}{2}\rho v^3 \pi R^2) \tag{2.16}$$

where R is the turbine radius, v the wind speed and ρ the density of the air.

Centrifugal Pumps

For applications requiring a low head, such as irrigation and drainage, a combination of wind turbine and centrifugal pump is better than the double acting piston pump. The efficiency of a centrifugal pump is, however, especially sensitive to variations in rotational speed.

According to Gasch et al (1987), a centrifugal pump offers the following advantages:

1. it is relatively unaffected by water impurities,
2. it is less affected by dry running than its piston equivalent,
3. it operates smoothly without any oscillating parts,
4. at very low wind speeds, around 2.5 m/sec, the piston pump delivers more water. At high wind speeds however the centrifugal pump is almost twice as efficient.

Gasch et al (1987) went on to present a simple method for the design of wind turbines with centrifugal pumps. Usually wind turbines are described by dimensionless numbers. The power coefficient, C_p, plotted against the tip speed ratio λ gives the performance characteristics of the wind turbine.

For any given performance and tip speed ratio the following relationship can be determined:

$$P = 1/2\rho \; C_p(\lambda)v^3\pi R^2 \tag{2.17}$$

where:

$$\lambda = \frac{2\pi nR}{v} \tag{2.18}$$

and where n is the rotational speed of the turbine in revolutions per second.

$\overline{C}_m$, the torque coefficient, can be calculated by equation 2.19:

$$C_m = C_p / \lambda \tag{2.19}$$

Gasch et al (1987) showed the total head, H, as a function of the capacity, Q, for the three basic types of centrifugal pumps, that is, radial, mixed flow and axial. They also showed the optimal values of the pressure coefficient, flow coefficient, and performance coefficient for these types of centrifugal pumps.

A near perfect matching can be obtained over a considerable speed range of wind speeds when using centrifugal pumps. This enhances the economic feasibility of electric transmission systems. Such a matching can be obtained because both the wind turbine and the centrifugal pump have cubic power speed curves (Goezinne & Eilering, 1984).

2.28.2 Wind Electrical Pumping Systems

A useful article by Goezinne and Eilering (1984) described a systematic design procedure for wind electrical pumping systems where the wind generator is directly connected to the electric pump. One begins with the wind and water data at the location under consideration. Knowing the desired output and the static head the required hydraulic power can be found. Next, by consulting catalogues a suitable pump and generator can be chosen. The gear box ratio mainly depends on the optimum speed of rotor and generator, so therefore the rotor then needs to be chosen. A complete matching procedure can then be carried out for the rotor and its load by consulting the power speed curves of both the rotor and its load.

Goezinne and Eilering (1984) provided a procedure for relating the flow to the wind speed with and without the assumption of a constant tip speed ratio. A turbine operated at a constant tip speed ratio, coupled to a permanent magnet alternator, which is ideally suited to centrifugal water pump (Ramakumar, 1983).

2.28.3 Pneumatic Pumping System

Feitosa et al (1989) described a water pumping system based on air pressure. This is especially useful where it is difficult to obtain straight bores. In arid regions of the world the high salinity of the water, often combined with the non verticality of the wells, make it difficult to use conventional wind driven pumping systems. Centrifugal pumps, in these situations, often suffer from high capital and maintenance costs, and often can suffer from serious corrosion.

A pneumatic pumping system offers the following advantages:

1. The pneumatic piping can be of practically any length. This means that both the wind turbine and the well can be situated at the sites best suited to them.
2. These pumps are highly economical in terms of operational and maintenance costs. They have no moving parts in the well and therefore require very limited maintenance.
3. No mechanical link is required between the pump and the rotor.
4. All components in contact with the water can be made of plastic (this is especially advantageous in arid countries where the pH of the water is often less than 6.0. Mild steel piston rods can lose 0.5 mm per year in such water). The wind turbine has a free starting torque which results in a much improved overall efficiency.

(Feitosa et al, 1989)

2.29 Tank Storage Requirements

One of the problems of wind pumps is that the output is not constant over time. This can be overcome by including a storage tank in the system. A model, in van Dijk (1986), can be used to determine the amount of storage capacity required. This calculation model uses another well established model to transform the hourly wind speed data collected over a year. These figures are then compared with the hourly water demand of an irrigated farm. In this manner, the extent of any deficit occurring can be calculated. Optimum storage tank capacity is normally in the order of one to two times the average daily wind pump output (van Dijk, 1986).

2.30 Transmission

Because many commercially manufactured wind pumps need to be located directly over a water source many opportunities for applying wind pumps are lost due to difficulties is siting the wind turbine. There are often very significant benefits to be had from separating the turbine from its pump.

Frankel (1987) examined the different methods of transmitting energy from one location to another. The most attractive transmission systems were determined as being mechanical, electric, hydraulic (using water) and pneumatic.

WATER POWER

Literature Review

2.31 Introduction

The earliest design of a water wheel consisted of paddles mounted on a vertical axis which was then lowered into a stream so that there was a greater current falling on one side. A significant advance occurred in 1880 with the invention of the Pelton wheel. A further major advance was the invention of the Kaplan turbine in 1917 (Dunn, 1986). At one stage during the 19th century, water power was so popular that there were over 20,000 water wheels operating in England alone (McGuigan, 1978).

Hydro power is a more concentrated source of energy than solar or wind power and therefore can generally be extracted more economically than other forms of renewable energy if a suitable site can be found (Dunn, 1986). Water power has been proven to be reliable, relatively low cost, durable, long lasting and easily maintained (Fraenkel, 1990). Most micro-hydro stations have a better record in terms of operation and maintenance than even diesel generators (Lazenby, 1991). With careful selection and engineering micro-hydro competes very well with diesel generators and extension of the grid for many situations (Holland, 1986).

Micro-hydro systems are now available for very small flows of around two litres per second with a head of about 50 m, or conversely for 50 litres per second flow down a 2 m head (Fraenkel, 1990).

2.32 General Comment on References

Two particularly useful books is this area are Fraenkel et al (1991), and Inversin (1986). The theory of micro-hydro power is thoroughly examined within Massey (1970). Giddens (1986) examined various aspects of micro-hydro power generation such as the construction of penstocks and intakes, and system governing and control. The control of micro-hydro systems is examined in more detail by Hagan (1986).

2.33 Types of Water Motors

The main types can be classified into water wheels, reaction turbines and impulse turbines.

2.33.1 Water Wheels

The efficiency for these is very low so they are not often used where efficiency and cost are key considerations. They also require substantial gearing because the speed of rotation is so slow.

There are two main types of water wheels: the undershot and the overshot wheel. MAF Aglinks AST 64 and AST 62/4 deal with the design criteria for these two types of water wheels.

Undershot Waterwheel

Undershot wheels are easily damaged by debris carried along by the stream and they suffer from a very low efficiency of generally less than 40% (Harrison-Smith, 1985).

Overshot Waterwheel

One of the advantages of the overshot is that it is self cleaning. Usually their efficiency is about 60 to 65% (McGuigan, 1978).

2.33.2 Impulse Turbines

In these machines almost all of the energy in the water is converted into kinetic energy. The water emerges from a jet at a high velocity but at atmospheric pressure. The three types of impulse turbines of particular interest are the Pelton wheel, Turgo turbine and the Crossflow (which is also called the Crossflow, Banki or Ossberger) turbine (Harrison-Smith, 1985).

Cross flow turbines and multi-jet Pelton wheels are often used for micro-hydro systems in remote areas because they are especially suitable for a wide range of site conditions and power outputs. This is because they normally use a belt or gearbox drive as speed increasers to extend the useful head and power range.

Advantages

For micro-hydro applications impulse turbines are used more frequently than reaction turbines because of their simplicity of construction and their good part load efficiency. This latter factor is a particularly important consideration where no storage system is used (Dunn, 1986). Another major advantage of an impulse turbine over a reaction turbine is that cavitation will not occur on an impulse runner or its casing.

General Disadvantages

Impulse turbines have a lower peak efficiency compared to reaction turbines (Hothersall, 1984).

Pelton Wheels

This type of turbine is generally selected for conditions of high head. With this type of turbine high pressure water is forced from a narrow nozzle to produce a high velocity jet. This jet strikes the buckets tangentially to the disc. Ideally the water should leave the buckets with no kinetic energy left at all. Large pelton turbines can have several jets and can be used for heads from 16 m to 500 m (Dunn, 1986; McGuigan, 1978).

Pelton wheels are perhaps the easiest of all small water motors to regulate (Harrison-Smith, 1985). MAF Aglink AST 65/7 provided a basic design criteria of the Pelton wheel.

Turgo Turbines

The Turgo impulse turbine is an improvement on the Pelton wheel, offering the following advantages:

1. It is only half the diameter of the Pelton wheel therefore runs at twice the speed. The necessity for gears is therefore greatly reduced. It also enables a more compact and less expensive generator to be made.
2. It is in use all over the world and has a reputation for trouble free operation (McGuigan, 1978).
3. It can operate at heads ranging from 15 to 300 m.
4. It can operate in silt laden water suffering only minimal wear. It has no fine clearances and any wear on the runner will not effect its efficiency. Under such conditions the most vulnerable parts are the needle valve and the deflector plate, both of which can be easily repaired or replaced.
5. All working parts including the governing reflector are easily accessible for maintenance.

Speed load control is carried out by jet deflectors which are governor operated. This means that there are no penstock shock loads.

6. The Turgo's design performance curve shows a high efficiency over a wide flow and load variations.

(Expanding by Staying Small, 1987)

Crossflow Turbine

This type is particularly well suited to low power and low head applications (Dunn, 1986). A second advantage of the crossflow system is that it is not susceptible to cavitation. Another is that leaves and other rubbish can pass through. An article in the *New Zealand Farmer* by Harrison-Smith (1982) described the procedure of the construction of such a turbine while MAF Aglink AST 66/8 described the design criteria.

Centrifugal Pumps as Turbines

Engeda and Rautenberg (1988) examined the suitability and design features of centrifugal pumps operating as turbines.
Hothersall (1984) provided formulae and conversion factors to relate the flow rate, head and the efficiency of pumps when used as turbines however these must be used with caution and only where test turbine data is unavailable. Hline and Wibulaswas (1987) provided similar conversion factors.

A convenient and quick method of choosing a suitable pump to operate as a turbine for a given situation is described in section 8.10 of this thesis. The disadvantages of operating pumps as centrifugal pumps were described by Engeda and Rautenberg, and is discussed in section 8.10.1.

2.33.3 Reaction Turbines

With these turbines only part of the part of the total potential energy is converted into kinetic energy before entering the turbine. These turbines are better suited to large flows of water in low head situations (Dunn, 1986). Their higher specific speeds means that they can be designed more compactly. Draft tubes can be used to utilize some sites more effectively (Hothersall, 1984). The disadvantages associated with them include the fact that maintenance can be more complex and expensive than on impulse turbines. Their application and operation is also sometimes limited by cavitation.

Francis Turbine

Although these are the traditional choice for heads of 6 to 100 m, very small Francis turbines can be problematic. They are constructed as a single unit so everything must be replaced if something goes wrong. The also suffer from cavitation and require very fine clearances for the moving parts (McGuigan, 1978).

Kaplan Turbine

An article by Lugaresi and Massa (1988) looked at the advantages of Kaplan turbines over Francis. It gave formulae for calculating the specific speed, cavitation coefficient and runner size. Schweiger and Gregori (1987) examined trends in the development of Kaplan Turbines. The data in this article can be used for a reliable and quick estimation of basic Kaplan parameters.

The selection of the basic Kaplan turbine parameters, especially the right choice of turbine specific speed, presents many economic and design problems. The positioning of the turbine runner with regard to the tail water level is particularly critical as it is linked with the civil works cost and with cavitation phenomena (Schweiger & Gregori, 1987). These authors go on to describe the relationship between head, energy coefficient, flow coefficient, peripheral velocity coefficient, diameter ratio, and height ratio, specific diameter, and the specific speed in a graphical form (Schweiger & Gregori, 1987).

2.33.4 Rams

Dunn (1986) described the principle on which these operate. Potts (1979) discussed the performance and construction of a home made ram. MAF Aglink AST 67 examined their design more closely.

2.34 Selecting the Most Appropriate Type of Turbine

This topic is addressed more fully in section 8.6 of this thesis.

Gosschalk and Bristol (1989) described a system designed for the preliminary selection of small micro-hydro systems in Indonesia however it is thought to be suitable for larger or smaller projects in other regions. A suitable site was identified using maps, existing reports or surveys. A reconnaissance survey was then carried out by a multi-disciplinary team of a civil engineer, hydrologist and a geologist.

The results of a paper by Schweiger and Gregori can be used for a quick estimation of basic turbine parameters for both axial and radial turbines. It also gave a formula for calculating specific speed. An article written by Hothersal (1984) provides a very good overview of the selection process.

2.35 Electricity Generation

Harrison-Smith (1985) devoted a chapter to the generation of electricity by water turbines.

2.35.1 Speed Control

Holland (1985), McGuigan (1978), and Giddens (1986), all addressed this issue. Section 8.16 should be consulted for more detailed information about this.

An article by Bryce and Giddens (1985) examined the different ways micro-hydro plants used for electricity generation can be protected from electrical malfunction. This is examined at four levels: consumer circuit protection, consumer mains protection, transmission line and the generator. It examined excess current protection, speed control, voltage control and human protection. Hagan (1986) presented an extensive article about the developments in controls for both mini and micro-hydro systems.

2.35.2 DC Power

An advantage of DC power is that no governor is required for its generation. It is often used for low output turbines where the current is fed straight to batteries. Power can also be taken from the batteries through a solid state inverter which provides AC current at whatever voltage is required (McGuigan, 1978).

The following problems associated with DC power systems have been described by Traeder (1986). They can suffer from electronic faults, synchronisation problems, frequency control difficulties and are sensitive to dust, high temperatures and humidity.

2.36 Costs

Locally made turbines used in many countries are often 70 to 80% efficient. Improving this efficiency is subject to the law of diminishing returns. An analysis of international publications indicates that the cost per kW of installed micro-hydro capacity varies from US$400 to US$3700 (Mikhailov,1990).

2.37 Developing Country Applications

Micro-hydro is a low cost technology which can, through the provision of power, help create industries and therefore, employment, in developing countries. An article written by Holland (1986) surveyed the criteria used in selecting equipment for micro-hydro plants in developing countries. Meier and Arter (1989) presented recommendations for people working with micro-hydro in remote areas. Some of their recommendations are shown below:

1. assessment of the flood risk and to dimension the plant flow measurements for at least one year is essential,
2. pilot programmes should aim at finding technical solutions,
3. all activity should be carried out with a motivated local partner,
4. simple projects, such as mechanical applications should be undertaken for the first experience of direct driving. Impact monitoring after the plant has gone into operation is essential,
6. long term activities should be the focus.

Robinson (1988) wrote about his varied experience with a particular micro-hydro system in Papua New Guinea. This helpful article gives insight into some very practical areas seldom touched on by other authors. Giddens (1986) discussed the appropriate use of micro-hydro technology in developing countries. He suggested that effective cooperation between engineers and the social scientist will often produce better results.

2.38 Conclusions from Literature

During the course of the literature review it was confirmed that while there was a lot of information about various aspects of renewable energy system design, there was very little information about overall system design and sizing. In particular there was a lack of literature addressing the issue of determining what type of renewable energy is the most appropriate for a given situation.

The following chapters attempt to remedy this situation. The specific objectives of this thesis are outlined in chapter 3.

CHAPTER 3

OBJECTIVES

On the basis of the gaps in the literature discovered during the course of the literature review, and on the basis of the perceived need, the following objectives were determined:

1. To conduct an extensive survey of the literature relating to photovoltaic, wind and micro-hydro systems, with emphasis on the selection and design process.

2. To provide sufficient background theory in each energy form to allow an understanding of at least the key parts of the design steps subsequently presented.

3. To present important theory in electricity, energy storage, and mechanical transmission as it relates to the application of renewable energy forms.

4. To describe the process by which the demand for electricity and water over a specified time interval may be determined.

5. To provide a comprehensive guide to the various parts of the design process for each energy form.

6. To create a computer model with which to utilise the theory presented in the thesis to generate design charts.

7. To outline the process by which different energy forms with different lifetimes and different operating costs may be compared to one another in order to derive the true cost of producing energy by a given method, allowing the optimum method to be selected.

8. To provide an extensive reference list of the various publications on the subject.

Chapter 2 has examined the current literature in order to meet the first objective. In chapter two the basic theory and peripheral design considerations for each energy form has been presented, while decisive design theory is presented in the appropriate chapter (objective 2). Chapter 4 considers energy forms, transmission and storage of energy (objective 3). Chapter 5 considers the determination of the demand of either electricity or water (objective 4).

To meet the objective 5, the key parts of the design process for each energy form is dealt with in the appropriate chapter. The financial side of determining the most suitable energy form is examined in chapter 10 (objective 6). The bibliography provides an extensive reference on photovoltaic, wind and micro-hydro power (objective 7).

Limitations of the Study

The emphasis of this study is on the generation of electricity and the pumping of water as it was thought these two areas are currently the most important areas of application, as well as offering the most potential for future growth. Much of what is written can, however, be extrapolated to other applications.

Photovoltaic energy is the only type of solar power examined. Other low grade solar applications such as solar water heating, crop drying, solar stills etc are ignored.

CHAPTER 4

ELECTRICITY THEORY, TRANSMISSION AND STORAGE

4.1 Introduction

The production of energy, either in an electrical or mechanical form, is the goal of any renewable energy system. It is therefore expedient that at least the basic theory of both electricity and mechanics is understood.

This chapter examines firstly the theory of electricity and different electrical devices which are often used within electrical systems such as inverters and rectifiers. It discusses the main types of energy storage available and deals at length with battery storage. The second half of the chapter examines mechanical transmission, discussing both the theory and the components associated with such systems. Emphasis is on the modes of coupling such as bèlt and chain drives.

4.2 Voltage

Before an electric current will flow around an electrical circuit there must be a force to move the electrons. This is termed the electromotive force (emf) and is measured in volts (V) (New Zealand Technical Correspondence Institute, 1977). If the voltage needs to be used with no transformation then the generated voltage should match that of the appliances and equipment operated. Where direct current (DC) power is used the effective choice is either 12 or 24 V. It is usually not recommended to install a DC system over 24 V as there are a limited range of 'off the shelf' appliances available which will run on it.

Power losses are inversely proportional to the voltage squared so 24 V is often more appropriate than 12 V, especially for wind and micro-hydro systems. The losses in the wiring of a 24 V system are only a quarter of a 12 V system. This is especially significant where the electricity generator is some distance from where the power is required (Ministry of Energy, 1986)

4.3 Frequency

For most alternating current (AC) supply systems the required frequency will be 50 or 60 Hz. Generally this is not critical as most motors and resistive appliances can tolerate a wide frequency variation. The frequency of the AC power supply in New Zealand is 50 Hz. This is the same as in England and Australia, while the frequency of the USA power supply is 60 Hz (New Zealand Technical Correspondence Institute, 1977)

4.4 Waveform

Ideally this is a pure sine wave. Some inverters produce a modified square wave which may cause motors to overheat or cause radio interference (Charters, 1986).

4.5 Current

This is the rate of flow of electrons through a circuit and is measured in amperes. It is one of two types: either alternating current (AC) or direct current (DC). Direct current always flows in the same direction, conventionally shown as being from positive to negative, but in reality just the opposite. Alternating current changes its direction of flow at regular intervals.

Many electrical appliances, such as heaters and lights, work equally well with DC and AC. However AC is generally supplied throughout the country because it is easy to generate and it possible to step the voltage up or down cheaply and easily.

4.5.1 Direct Current

An advantage of DC power is that no governor is required for its generation, that is, the precise speed of the turbine and generator is not critical and so there is no need for expensive control equipment. It is often used for low output systems where the current is fed straight to batteries (McGuigan, 1978). A disadvantage of DC power is that it needs expensive rectifiers at each end of a system if the voltage needs to be altered. Because of this, AC is generally used for transmission.

Most DC power systems use a voltage regulator to protect the battery and the load appliance from excessive voltage. DC generators are available up to several kilowatts and are commonly used for applications of up to several hundred watts (Inversin, 1986).

4.5.2 Alternating Current

Where AC power is required there are two ways in which this may be achieved. Either an alternator may be used to generate it directly or DC power may be generated and stored in batteries and then an inverter may be used to convert this into AC. Where storage is not required the former alternative is preferable (Inversin, 1986). With an AC system there is usually a need to maintain frequency, and therefore speed of the turbo-generating unit within certain limits. Generally a governor or load controller is used for this purpose (Inversin, 1986).

AC: Single vs Three Phase

Single phase generators are available for the entire micro-hydro range while three phase generators cover the range down to about two to three kW. Single phase generators are commonly used with schemes less than about 10-15 kW. For small units the cost of generators is about the same. However a three phase unit requires costlier switch gear and control equipment.

The application may determine the number of phases to use. Single phase motors are available for most applications which require no more than 2.2 kW. For larger loads three phase motors tend to be used as the cost per generated kWh is less (Inversin, 1986).

4.6 Series vs Parallel Circuits[4]

4.6.1 Series Circuits

A series circuit consists of several parts where the end of one part is connected to the beginning of the next, and where the current must pass through all parts in succession as it flows around the circuit.

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[4]Refer also the section 4.15.3 on battery configuration

Series circuits have the following characteristics:

1. the current is the same in all parts of the circuit,
2. the total resistance of the circuit is equal to the sum of the total resistances of the individual parts,
3. the voltage applied to the circuit is equal to the sum of the voltages across the individual parts,
4. the voltage across each part is proportional to the resistance of that part.

(New Zealand Technical Correspondence Institute, 1977)

4.6.2 Parallel Circuits

Where two or more electric circuits are connected to a common source of voltage they are said to be in parallel. Parallel circuits have the following characteristics:

1. the voltage across each part is equal to the supply voltage,
2. the total current drawn is equal to the sum of the currents drawn by the individual parts,
3. the equivalent or total resistance is always less than the smallest resistance in the circuit

(New Zealand Technical Correspondence Institute, 1977)

Figure 4.1 A Parallel Circuit (New Zealand Technical Correspondence Institute, 1977)

4.7 Inverters

Power can be taken from the batteries and run through a solid state inverter to provide AC current at whatever voltage is required (McGuigan, 1978). The economic viability of low voltage electricity storage using batteries has markedly increased with the relatively recent introduction of high quality inverters (Ministry of Energy, 1986). These are simple devices which convert low voltage DC electricity (such as that produced by batteries) into 230 V AC.

There are two main types of inverter, the rotary and the solid state. The main advantage of the rotary inverter is that it can cope with the initial surge experienced when electric motors are started. It also produces a pure sine wave output (Ministry of Energy, 1986).

4.8 Rectifier

This is a device which converts AC to DC. It is commonly made up of semi-conductor diodes which conduct electricity in one direction only. Differing degrees of complexity are available depending on how important it is to achieve a steady direct current (New Zealand Technical Correspondence Institute, 1977). Where an alternator is used to charge a battery the current must first pass through a rectifier.

4.9 Transformers

A transformer basically consists of two windings magnetically linked by an iron core. It transfers the energy from one circuit to another by electromagnetic induction. The energy is always transferred without a change in frequency but usually with a change in voltage or current (New Zealand Technical Correspondence Institute, 1977). An exception is where it is used for safety reasons. In this case a one to one transformer is used which prevents a circuit being formed when someone comes into contact with a live appliance. The current must be AC if a transformer is able to be used.

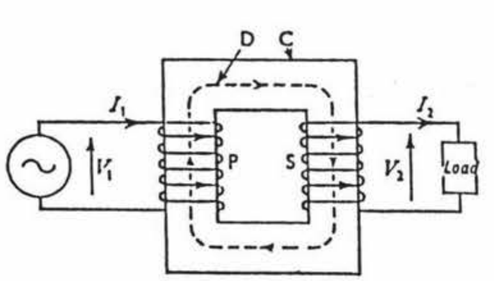

Figure 4.2 A Transformer (New Zealand Technical Correspondence Institute, 1977)

A medium size transformer has an efficiency of about 97-98%. It is reliable and, because it has no moving parts, requires minimal maintenance (Hughes, 1977). The inductance[5] of a coil is proportional to the square of the number of turns.

Transformers can be used to step up or step down both voltage and current (Hughes, 1977). The relative voltage is primarily determined by the number of windings present on each side where:

$$\frac{V_s}{V_P} \approx \frac{N_s}{N_p} \qquad (4.1)$$

where the load is switched on any variation in the secondary current is accompanied by a proportional variation of the primary current. Therefore equation 4.2 applies.

$$\frac{I_p}{I_s} \approx \frac{V_s}{V_p} \approx \frac{N_s}{N_p} \qquad (4.2)$$

where:
I_p = primary current
I_s = secondary current
V_s = secondary voltage
V_p = primary voltage
N_s = secondary turns
N_p = primary turns

(New Zealand Technical Correspondence Institute, 1977)

The power rating of the transformer can be determined by the equation 4.3:

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[5]Inductance is the effect of a magnetic field being produced around an electric current, which then can interact with other magnetic fields (New Zealand Technical Correspondence Institute, 1977)

$$Power\ Rating = I_p V_p = e\, I_s V_s \tag{4.3}$$

where e is the efficiency of the transformer.

To sum up, the voltage varies in proportion to the number of turns, while the current is inversely proportional to the voltage, and therefore the number of turns.

4.10 Generators

For successful design of a remote area power system particular attention must be given to the alternator or generator (Watson et al, 1983). All electrical generators work on the principal of electro-magnetic induction. The simplest form of generator, illustrated in figure 4.3, consists of a single loop of wire supported and rotated at constant speed between the north and south poles of a permanent magnet. The slip rings are the circular rings of metal on which the brushes bear. Such a generator produces AC current and therefore this type and all other generators which produce AC, are called alternators. In practice an electro-magnet is often used instead of permanent magnets (Massey University, 1990). The permanent magnet generator has the advantage of not needing to supply power to the field and therefore has a higher inherent efficiency.

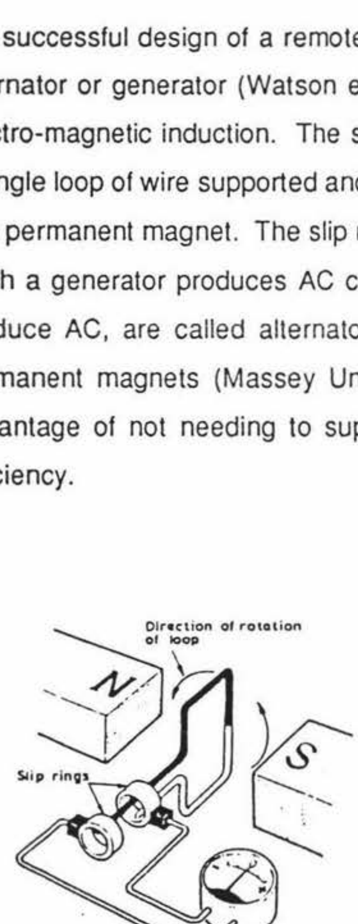

Figure 4.3 A Simple Generator (New Zealand Technical Correspondence Institute, 1977)

This type of generator is recommended for constant voltage operation up to a power rating of 2000 W (Menzies et al,1980). It is however not normally grid connected (Smith & Nigim, 1988) although this is usually of little consequence for remote area power systems.

An AC generator can be modified to produce DC instead of AC. This can be done by replacing the slip rings in the AC generator with a two segment commutator similar to what is used in a simple electric motor, as shown in figure 4.4.

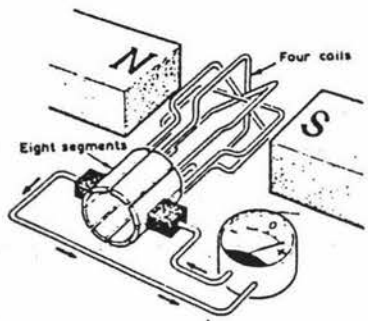

Figure 4.4 A Multi-Coil Generator (New Zealand Technical Correspondence Institute, 1977)

Here each single coil is linked with a pair of commutator segments. This wave form pulsates slightly, however, in practice is indistinguishable from the DC produced from a battery.

4.10.1 Sizing the Generator

Generator size is specified in kilovolt-amps (kVA) rather than in kW. Where the load is purely resistive, the current and the voltage will be in phase and therefore the kVA will equal the kW of the system. For other loads such as motors, the voltage and current may not be in phase. In this case the effective power required will depend on the extent to which the voltage leads the current. The parameter used to make this adjustment is termed the 'Power Factor' where:

$$Power = Volts\, x\, Amps\, x\, PF \tag{4.4}$$

where PF is the power factor.

Example: Where a load with a power factor of 0.7 is connected to a generator of 240 V, a 2 kW load will draw 12 A.

2000 / (240 x 0.7) = 12 A

A purely resistive 2 kW load would draw 2000 / 240 = 8.3 A. In both cases, however, 2 kW of power is consumed, yet in the design of the generator and in the choice of wiring the actual current drawn needs to be 12 A (ie 45% greater).

4.11 Motor Selection

An induction motor generally performs satisfactorily over a range of plus or minus 10% from the rated voltage and plus or minus 5% from the rated frequency. The torque developed by the motor is roughly proportional to the square of the voltage and inversely proportional to the square of the frequency (Vosper & Clark, 1988).

Permanent DC motors are normally regarded as being the most suitable for use in photovoltaic systems where no battery storage is to be used. The reason for this is that they are reliable, have a reasonably low cost and can operate over a wide range of input voltages (Pulfrey et al, 1987). DC motors may, however, be more than twice as expensive as AC motors although this is partly offset by the cost of the inverter required for an AC motor (McNelis, 1986).

4.12 Wiring

The three wires in a household appliance in New Zealand are the: phase (red or brown); neutral (black or blue); and earth (green or yellow and green stripes). Care needs to be taken to ensure the neutral and phase wires are not interchanged. When this occurs the appliance will still operate but the frame could become electrically live (Massey University, 1990).

4.13 Voltage and Power Drop Along a Wire

All conductors used in the transmission of electrical energy have resistance. The resistance of a particular conductor is related to its cross sectional area, its length, and the material from which it is made.

Copper wires are almost exclusively used for conductors for remote area power installations although occasionally aluminium wire may be used. Aluminium wires should only be used outside because they have apparently been the cause of many electrical fires (Marier, 1981). Table 4.1 shows the resistance and rating of different sizes of copper wire.

Table 4.1 Copper Wire Resistance and Rating

Cross Sectional Area (mm^2)	Resistance per 100 m for two wires (ohms)	Maximum Current Rating (amps)
1.0	4.2	10
2.5	1.5	20
4.0	0.92	25
6.0	0.62	*

(adapted from Tamar Designs)

It is important to consider the line voltage drop and to relate that to the cost of the wire used. Some appliances are more able to tolerate voltage drops while others such as computers and TV receivers cannot. It is recommended that the voltage drop be kept to below 5% and as low as 2%, if possible (Marier, 1981).

The line voltage drop is a product of the current and of the resistance of the line.

$$Voltage\ Drop = Current(amps) \times Resistance(ohms) \tag{4.5}$$

So, for example, with a 2.5 mm^2 cable carrying 4 amps over 200 m, the voltage drop is:

$$4 \times (1.5 \times 2) = 12\ V$$

The power loss (W) incurred in transmission can be calculated from the resistance of the line and the current flowing in that line.

$$\begin{aligned} Power &= amperes^2 \times resistance(ohms) \\ P &= I^2 \times R \end{aligned} \tag{4.6}$$

In the above example this is:

$$= 16 \times (1.5 \times 2)$$

$$= 48\ W$$

A figure of 5% is commonly regarded as the maximum allowable transmission loss (Tamar Designs). Transmission losses are mostly dependent on current. When the current doubles, the power losses are quadrupled. This is why for trasmitting power large distances, high voltage lines are used. Higher voltage means lower current (Watts = volts x amps) which means lower resistance and so lower transmission losses.

4.14 Safety

The severity of an electric shock depends on the amount and duration of current flow through the body. An alternating current of 0.1 ampere is almost certain to be fatal if it passes through the vital organs of the body (New Zealand Technical Correspondence Institute, 1977). Assuming that the total electrical resistance of a person is about 1000 ohms, an AC voltage of 100 V is potentially very dangerous (V = IR). The danger is further increased where the resistance is decreased such as when the victim is very well earthed or has wet skin.

4.15 Types of Energy Storage

At one time wood piles and dams were the only means of storing energy. Today there are many methods which can be used such as heat, chemical, mechanical, and electrical means (Jensen, 1980). The nature of the most appropriate type of storage will vary depending on the energy source and the application. However regardless of the type of energy the two crucial features of any storage system are: the amount of energy to be stored; the duration for which that storage needs to be maintained (Jensen, 1980).

In practice there are only a few forms of energy storage in common use with remote area power systems. Ranked in order of usage they are:

1. battery storage,
2. water storage,
3. flywheel storage (with diesel generators).

4.16 Battery Storage

Small wind and photovoltaic systems almost always require some form of energy storage and this is usually in the form of lead-acid batteries (Todd, 1987). Where the form of energy produced is already electrical, such as with photovoltaic systems, batteries are the logical choice.

Advantages of Battery Storage

Incorporating batteries into the system offer the following advantages:

1. they provide energy when no energy is being produced by the system,
2. they help meet short term peak demand,
3. they help stabilise the system voltage,
4. they reduce energy loss by providing a means of energy storage,
5. they are modular and reasonably transportable,
6. they are readily available.

(The first two advantages are not solely associated with battery power)

Disadvantages of Battery Storage

Batteries suffer the following disadvantages:

1. they add to cost and complexity of a system,
2. they increase maintenance requirements,
3. they may reduce system reliability,
4. they contain acid which is susceptible to spillage,
5. they give off hydrogen which is explosive,
6. they are heavy,
7. they require regular maintenance.

(Groumpos & Papageorgiou, 1987)

Sealed batteries are available which do not have the fourth and fifth disadvantages associated with them. An example is the relatively new type of battery in which the electrolyte is absorbed by the plates. One of these is marketed under the name of 'GNB Absolyte'.

This type of battery offers many advantages over the conventional lead acid battery such as:

1. being totally sealed it is able to be mounted horizontally or vertically,
2. it is relatively light as well as compact,
3. it never requires watering, neither does it vent potentially dangerous hydrogen gas,
4. it can be frozen without significant damage to the cells.

(Mayer, 1985)

4.16.1 Battery Types

The type of battery most appropriate for a given application will depend on the application. For example, a wind electrical system is able to give equalising boost charges, while solar systems tend to be continuous shallow cycling (Watson et al, 1983)

For deep cycle applications, deep cycle lead acid batteries are the only type which are suited to remote area power supply in New Zealand. Nickel-Cadmium batteries are not yet cost competitive with the lead acid type (Ministry of Energy, 1986). They would however offer several advantages. Table 4.2 compares these two batteries.

The electrode reactions in all lead-acid batteries are effectively the same. As the battery is discharged, the lead dioxide positive active material and the spongy lead negative material both react with the sulphuric acid electrolyte to form lead sulphate and water. During charging this process is reversed (Absolyte 2 Battery Product Manual).

4.16.2 Battery Capacity

This is measured by ampere-hours (A.h) and is the quantity of discharge current available for a specified length of time at a given discharge rate. For example, a battery rated at 100 A.h can deliver 5 amps per hour for 20 hours.

To obtain the amount of storage capacity in W.h or kWh, one can multiply the battery bank voltage by the A.h value. For example, a 180 A.h, 12 V unit has a capacity of 12 V x 180 A.h = 2160 watt hours, ie 2.2 kWh.

Table 4.2 A Comparison of Lead-Acid and Nickel-Cadmium Batteries

	Lead-acid	Nickel-cadmium
Type	Medium rate, deep discharge, lead-calcium grid	Medium rate, cycle service, vented pocket plate
Rated capacity at 77 °F, 8 h	100-900 A h per cell	10-400 A h per cell
Nominal discharge cut-off voltage	1.75 V per cell	1.0 V per cell
Nominal voltage	2.45 V per cell, varies with state of charge	1.25 V per cell, fairly constant with state of charge
Available capacity against temperature (% of rated capacity)	70% at 32 °F 20% at −20 °F	90% at 32 °F 65% at −20 °F
Nominal energy efficiency	70-80%	60-70%
Nominal cycle life for 80% discharge cycle	1000-1500	1500-2000
Nominal calendar life without cycling	10-20 years	24 years
Energy density	6-13 $W\,h\,lb^{-1}$	9-10 $W\,h\,lb^{-1}$
Required maintenance	Water replacement; charge equalization; protection against freezing and temperature extremes	Water replacement; occasional full discharge
Charge control	Sensitive to overcharging	Can accept 5-10% overcharge
Hazards	Electric shocks; hydrogen gas evolution; acid leaks or spills	Electric shocks

(Lasnier & Ang, 1990)

Since most batteries are only about 85% efficient one can allow for battery losses by adjusting the battery capacity, or by adding 17.5% onto the demand and then calculating the storage as if the battery were 100% efficient.

Example: If there was a storage requirement of say 5 kWh per day for a period of three days, then the battery capacity required will be:

3 days x 5 kWh (x 1.175) = 17.6 kW

Now if the system is a 24 V then the capacity required is

17600 / 24 = 733 A.h

To allow for wire losses, in addition to battery inefficiencies, it has been suggested that a total figure of 20% is used (Ministry of Energy, 1986).

Effect of Temperature

A lead-acid battery's storage capacity decreases about 1% for every 1°C drop in temperature below the rated temperature (usually 25°C). Figure 4.5 enables this to be corrected.

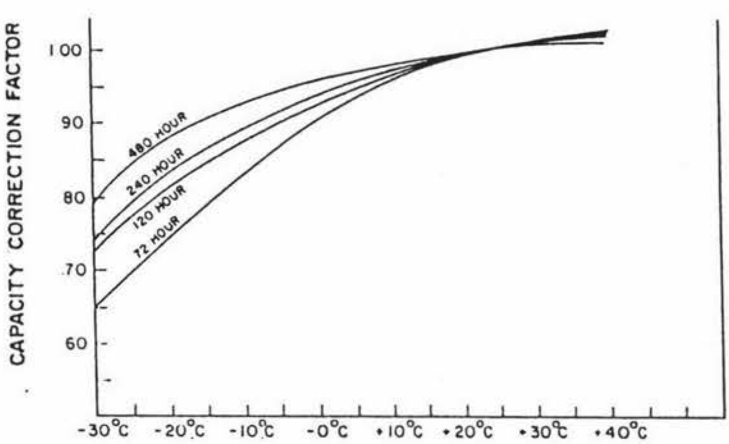

Figure 4.5 Battery Capacity Correction for Temperature (Lasnier & Ang, 1990)

The battery's rated capacity at 25°C needs to be multiplied by the correction factor to yield the expected battery capacity at a given temperature. When ambient air temperatures are used the temperature readings over a 24 hour period should be averaged.

4.16.3 Battery Configuration[6]

Batteries can be connected in series to increase the voltage, or in parallel to increase the current. Both increase the storage capacity, although it is preferable to use higher amp-hour batteries in series to increase capacity (Ministry of Energy, 1986). Where batteries are connected in parallel they should always be separated by a fuse or diode[7] as illustrated in figure 4.6. Batteries of different ages or capacities should never be connected in series or parallel or otherwise the weaker batteries will tend to drain the fresher ones.

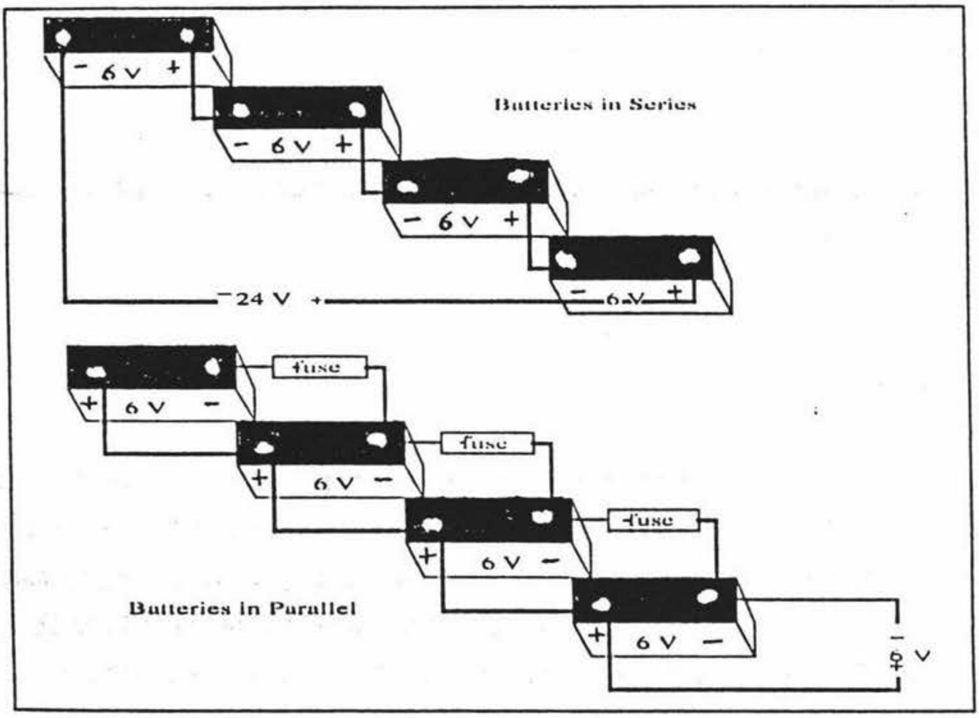

Figure 4.6 Series and Parallel Battery Configurations (Ministry of Energy, 1986)

4.16.4 Discharging Lead Acid Batteries

The maximum rate for continuous discharge of a battery is approximately 10% (Ministry of Energy, 1986). For example a 720 A.h battery should not have more than 72 amps drawn from

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[6]Refer also to section 4.5 on series and parallel circuits

[7]A diode allows current to only flow one way.

it continuously. The discharge rate influences the total capacity as shown by figure 4.7. To maximise battery life, depth of discharge (DOD) should be restricted to 50% although this will vary depending on the type of battery. To enable comparisons to be made between batteries, four different cycles are often specified (ie 80%, 50%, 30% and 10% depth of discharge).

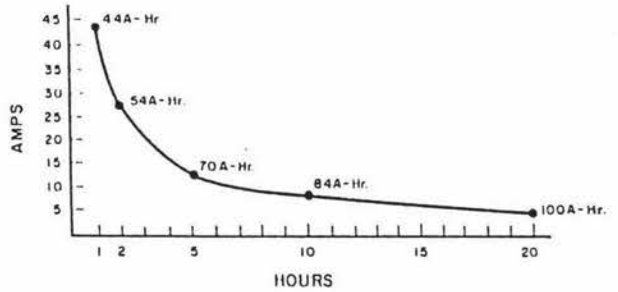

Figure 4.7 The Relationship Between Ampere-hour Capacity and Discharge Rate (Exide Battery Promotional Material)

4.16.5 Recharging Batteries

The amp-hour efficiency of recharging normally lies in the range of 80% to 95% of full charge (Exide Battery Promotional Material). Batteries should receive regular boosting to prevent the electrolyte from separating out into layers of different density. The optimum recharging voltages will depend slightly on the ambient temperature if this is not within the range of 25 to 35°C. In this case the manufacturer's catalogue should be consulted. Typically, the correction factor is only about 5 millivolts per degree (Exide Battery Promotional Material 1).

4.16.6 Battery Life

Some modern batteries designed specifically for remote area applications have an expected life of 2500 cycles to 50% depth of discharge (Exide Battery Manual). Battery overcharging will significantly reduce the life of the battery. This is often a problem with photovoltaic systems, while proper maintenance can significantly add to the life of a battery.

4.17 Water Storage

This form of storage is one of the most simple means of storing energy and is commonly used with micro-hydro systems where there is an ample supply of water and the topography is suitable for dam construction. Overall energy recovery in such systems is often 80-90% (Dunn, 1986).

Water storage is also occasionally used with wind and photovoltaic pumping systems where the output is pumped directly into a water storage tank. A tank provides storage when water supply exceeds demand. This water can then be drawn on when demand exceeds supply. Commonly, such tanks are elevated which enables water from them to be gravity fed. Elevation in this manner is only practical where water is the desired product rather than electricity, because to produce a mere 1 kWh requires 36500 l to fall through a height of 10 m (if the process was 100% efficient).

4.18 Flywheel Storage

It has been suggested that the best way to store energy in a flywheel is to make it of wood and then to set fire to it (Dunn, 1986). A flywheel can, however, be successfully used to store energy. Flywheels are in fact ideally suited to the rapid power fluctuations commonly associated with wind systems (Davies et al, 1988). The amount of energy stored is proportional to the speed of rotation of the flywheel.

Some advantages of using flywheels are: they reduce the number of stop and start cycles performed by the diesel generator and therefore prolong its life; they have a high efficiency; they have an almost infinite cycle life; they are compact and have a fast response. Their main disadvantages are: they significantly add to the complexity of control equipment required, they require some sort of bilateral transmission system; and they are only suitable for very short term periods of storage (Ramakumar, 1983).

For a storage system to be successful it must be able to do the following:

1. smooth out the effective power output from the power source,
2. sustain the load power during short term dips in power output,
3. sustain the load power demand, if power source has dwindled, long enough to allow the diesel generator to start.

(Davies et al, 1988)

4.19 Pneumatic Storage

This is where the electrical output of a wind water turbine is used to drive a compressor to compress air for storage in tanks or underground caverns. The stored energy can then be retrieved using turbines or piston engines. The overall efficiency of this method is rather low at about 30% (Ramakumar, 1983).

Basic Introduction to Aspects of Mechanical Transmission

4.20 Power

Power is a measure of the rate at which work is done and can expressed by equation 4.7. It may be measured in a number of units but horse power (hp) is still one of the most common. The SI unit of power is the watt or kilowatt (1 kW = 1000 W), where 1 hp = 746 watts (or about 3/4 kW). Brakepower is the useful power taken from a machine or engine and is also called power output (Patton, 1980). The kW is the preferred unit and is used throughout this study.

$$Power = \frac{Work}{Time} \tag{4.7}$$

4.21 Torque

Torque is defined as the turning effect. This involves two quantities, a <u>force</u> applied at a given <u>distance</u> from the axis of rotation. The distance the force is applied from the axis of rotation is termed the leverage. It is calculated by simply multiplying the force (N) by the leverage (m) with the resulting torque units of Newton metres.

Power is seen to be directly proportional to torque by the following equation 4.8:

$$Power = 2\pi TS \tag{4.8}$$

where:

T = torque

S = speed of rotation in revolutions per second

4.22 Speed of Rotation

Speed of rotation is also commonly measured in rpm (revolutions per minute). From equation 4.8 one can see that speed is directly proportional to power.

4.22.1 Speed Increase and Speed Decrease

Often the speed of revolution needs to be increased from that derived from a wind or water turbine. Gear trains and belt drives act as torque converters by altering speed. The same brakepower can only be maintained if the torque in the shaft, which has had its speed altered, is itself altered.

Example: Suppose a windmill delivers 5 kW (while rotating at 600 rpm) to a 20 cm V-pulley on a shaft. The V-pulley drives a 10 cm V-pulley on another shaft by means of a V-belt. The driven shaft will rotate twice as fast as the drive shaft but still receives 5 kW (ignoring any inefficiencies). It will therefore possess only half the torque of the drive shaft (Patton, 1980).

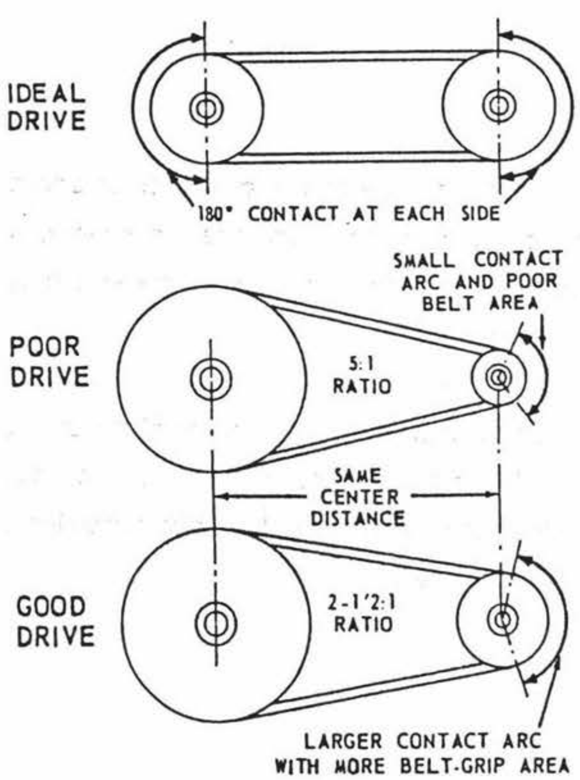

Figure 4.8 The Effect of Pulley Size on Drive Suitability (John Deere, 1980)

For full power on the belt, the pulley ratio should be no more than three to one. Higher ratios lessen the area of contact resulting in slippage and loss of power. Figure 4.8 illustrates this effect.

4.23 Friction

Friction is a force parallel to the sliding faces of two bodies in contact and arises from the resistance to movement caused by interlocking small surface irregularities on the two contacting surfaces. The friction force between two surfaces is proportional to the pressure between them.

The static coefficient of friction is greater than the dynamic coefficient of friction that applies once the body is in motion (Patton, 1980). This is readily shown by pushing a car: it is much more difficult to start the car moving than to keep it moving.

Evaluation of Components Associated with Mechanical Transmission.

4.24 Coupling

4.24.1 Direct Coupling

The optimum form of coupling is direct coupling of the turbine to the generator or driven machinery. This can, however, only be done when both operate at the same speed and they can be laid out so their respective shafts are co-linear. The advantages are obvious: the system is compact; efficiency is very high; and maintenance is minimal.

The main disadvantage of direct coupling is that a sudden change in load or speed of the turbine may result in major damage due to the inertia of the other rotating component. To overcome this, a flexible coupling made of rubber or elastic material is often employed. With direct coupling it is very important to ensure that the shafts are properly aligned.

4.25 Belt Drives

Belts are readily available and cheap and are therefore often used for coupling. Several types of belts can be used, including V-belts, flat belts, and timing belts.

4.25.1 V Belts

These are made in three main types, the standard V-belt, the heavy duty belt and the double angle belt. Each one is made of four main sections. The top section is called the tension section. The bottom section is called the compression section because it compresses when wedged into and shaped around the sheave. The centre section of the belt is known as the strength section and contains many pulling cords.

A heavy duty belt uses a different type of material for the cords. The whole belt is covered by some tough fabric and rubber.

The advantages of V-belts are:

1. wedging action permits a lower arc of contact on the small pulley and a large speed ratio,
2. shorter centre distances can be used for a compact drive,
3. shock is absorbed by elastic extension and slip to cushion motors and bearings against load fluctuations,
4. vibration and noise levels are low,
5. maintenance and replacements are quick and easy,
6. power transmission efficiency is as high as 95%.

(John Deere, 1980)

All of the above advantages can be important in wind and water turbine systems. With wind turbines especially shock loads can be experienced due to gusts, therefore the ability of V-belts to absorb shock and so cushion motors and bearings is a major advantage. The characteristic of quick and easy maintenance is particularly important for systems in remote areas or areas with difficult access. Where the power source is relied on for the provision of power or another essential service this reduction in down time is very important.

Where the unit is installed close to a dwelling the amount of noise emitted is also important. V-belt pulleys do require a greater degree of skill in their construction than do flat belts and this may be an important consideration for developing countries.

4.25.2 Flat Belts

These belts and their associated pulleys are simple to construct therefore are often the most appropriate for developing countries. One disadvantage of them is that to avoid slippage they must operate under a high tension which places an additional load on bearings shaft and mountings.

4.25.3 Timing Belts (also called position drive or gear belt)

Because timing belts are toothed and rely on mechanical coupling rather than on friction to transmit the power, they require only minimal tension. There is less friction and so their efficiency is higher than V-belts.

Their associated disadvantages are: they are more expensive; they are less common and therfore harder to find; and they are a lot noisier than V-belts. For these reasons they are rarely used with water and wind turbines (Inversin, 1986).

4.25.4 Belt Tension

Too little tension will cause belt slippage or slip-and-grab. This will either cause the belt to break or will cause excessive wear and overheating. Too much tension may cause damage to drive components such as sheaves and shafts as well as bearings (John Deere, 1980).

4.26 Chains

These have a very high efficiency of up to 99% because there is no slippage and minimal friction. They do not require tensioning and provide the option of a short centre distance. One of their associated disadvantages is their requirement of regular lubrication and being costlier than belts (Inversin, 1986), especially for low horsepower and low ratio applications (John Deere, 1980).

One of the main reasons that chains tend not to be used with turbines is that if the turbine or generator suddenly stops, damage usually occurs.

4.27 PTO Shafts

PTO shafts offer significant advantages for use in a transmission system. Some of these are:

1. an economic staggering of sizes so one need not pay for more than is required,
2. ability to compensate for movement, variations in angle and length,
3. large range of clutches, brakes and couplings available for use with these shafts,
4. ease of connection and removal.

The shaft's ability to compensate for movement is an advantage especially where a wind system incorporates a sizeable tower which is likely to move in a strong wind When a PTO shaft is used, it offers greater flexibility in the use of other power sources. For example a diesel generator can be used to replace the wind or water power when it is insufficient. The disadvantages of PTO shafts are that they are relatively expensive and that they require the use of specific types of couplings, brakes and clutches which may not be readily available in remote areas.

4.28 Gearboxes

Gearboxes enable gearing up or down to obtain the speed of revolution required for the particular application. Normally gearing up is required, particularly where electricity is to be generated.

Factors to consider in the selection of a gearbox include: the power transmission capacity; the maximum speed; the maximum ratio; the efficiency; the noise level; and economics. Gearboxes are about 98% efficient. Often, however, where a very precise gearing ratio is required, a gearbox may not be available with that particular ratio so it would be better to use V-belts. Most commercially available gearboxes are designed to reduce the rpm of the driver but it is not advisable to use such a gearbox in the reverse mode to increase rpm.

Where a PTO shaft is used gearboxes are available which are made to connect directly to this. This avoids any need for additional connections and makes coupling and uncoupling very fast. Gearboxes are more expensive than belts and do not cope with shock loads so well. Where such loads are expected, such as with wind systems, it is advisable to oversize the gearbox and incorporate a shear pin in the arrangement, or avoid the use of a gearbox altogether. Water turbines are more suited to use with gearboxes as the loads are more constant and can be more easily regulated.

If at all possible, it is better to avoid gearing as this in turn reduces complexity, losses, and the amount of maintenance required. While this is not generally a practical option with wind turbines, it can sometimes be done with micro-hydro systems by selecting a turbine that will run at the speed set by the machinery it is to drive. This will then enable direct coupling.

In practice new gear boxes are rarely used with micro-hydro systems because of their cost (Inversin, 1986). Second hand car gearboxes and differentials have been used successfully in conjunction with both water turbines (Inversin, 1986) and wind turbines (Wilson, 1978), although these tend not to be very efficient or very compact. Where a gearbox is used, special care should be given to the lubrication and sealing.

4.29 Brakes

Some form of braking is particularly important for a wind power system. Excessive wind could easily cause damage if the turbine is not protected in some way. Section 2.21 deals with this issue.

Micro-hydro systems do not require brakes per se but they do require that their speed is carefully regulated. Section 8.16 examines this.

4.30 Transmitting Power from Renewable Energy Sources some Distance

Often the optimum location for harnessing the power source is located some distance from the area where the power is required. This can often lead to the loss of many opportunities for harnessing renewable energy (Fraenkel, 1987). The four main options for transmitting power are: mechanical (using a shaft or cable), electrical (using AC or DC), water hydraulic, or pneumatic.

The summary in table 4.3, reproduced from Fraenkel (1987), illustrates advantages and disadvantages of the various means of transmitting power.

Table 4.3 A Summary of Conclusions on Transmission Options

Summary of Conclusions on Transmission Options.

Transmission	Mechanical	Electrical	Hydraulic	Pneumatic
Parameter				
Experience to date	Poor	Fair	Fair	Limited
Reliability in use	Poor	Good	Fair	Fair
Potential for local Manufacture	Good	Poor	Good	Fair
Adaptability/ Flexibility	Poor	Good	Fair	Fair
Safety	Poor	Poor	Fair	Good
Turbine Cost	Low	High	Low	Low
Transmission cost/metre	Low	High	Low	Low
Comparative Economics				
< 500m	Fair	Poor	Fair	Fair
> 500m	V. Poor	Fair	Poor	Good

(Fraenkel, 1987)

CHAPTER 5

DEMAND ASSESSMENT

5.1 Introduction

Before a renewable energy system can be designed, the power demand must be estimated as accurately as possible. This should ideally include an estimate of the average and peak load, and the load fluctuations over time. The accuracy with which this is done will determine how precisely the system can be matched to a particular requirement. Where the load is underestimated the system will be unable to keep up with the demand, while where the load is overestimated the system will be oversized, resulting in unnecessary expenditure.

This chapter first examines the determination of the electrical demand profile based on appliance ratings and considers the difference between average power consumption and the peak power consumption. It addresses the issue of water heating and water pumping with respect to the demand profile.

Assessment of water demand is then considered, examining domestic consumption, animal consumption and the water requirement for irrigation.

5.2 Determining the Demand Profile

The magnitude of the demand and its changes over time are referred to as the demand profile. For any given situation the demand profile is likely to be different. It can be assessed in the following manner:

1. the appliances which will be used are determined,
2. the power requirement of these appliances is determined (W)[8],

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[8] Appendix A provides useful figures regarding appliance power rating and energy demand

3. the consumption per day for each appliance is calculated based on the average time for which each appliance operates (kWh),
5. the total power consumption per day (kWh/day) is calculated by summing the individual loads,
6. the peak power load (kW) is calculated by adding the ratings of all of the appliances which might be operated together,
7[9]. the peak line current (amps) at line voltage is calculated by dividing the peak power load by the voltage.

Once this has been done all the information required to determine the average daily energy demand, average monthly energy demand, the annual energy demand and the average power load is present.

Table 5.1 is an example of this procedure for a remote dwelling, housing six individuals.

5.2.1 Daily Power Consumption

In table 5.1 the daily total power consumption is 13 kWh. This should be regarded as an approximate average daily consumption figure. This figure must be interpreted in conjunction with the peak power load figure for the renewable energy system sizing.

5.2.2 Peak Power Load

For a domestic daily demand profile there tends to be two main peaks for domestic consumption, one in the morning when people get up and wash etc, and the other in the evening when people cook, light and heat.

Peak load often can only be met through the use of some form of storage system or alternative energy supply such as a diesel generator. The size, and therefore the cost, of both systems is proportional to the difference between the peak and average demand. It is therefore important that the peak load be minimised in order to minimise the cost of a system.

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[9] Chapter 4 deals more closely with the electrical aspects of design

Table 5.1 Demand Profile based on Energy Demand for Six Individuals in a Remote Dwelling

Appliance	Approx Rating (W)	Hours use per day	kWh/day
Electric Clock	10	24	0.24
Coffee Machine	700	0.25	0.175
Colour TV	300	2	0.600
Freezer	200	11	2.2
Fridge	250	15	3.75
Hair Dryer	400	0.5	0.20
Heating	Wood only	na	0
Iron	1000	0.25	0.250
Jug	1500	0.25	0.375
Lighting			
-Incandescent	4x100	3.0	1.2
-Fluorescent	2x50	3.5	0.35
Stereo	100	0.75	0.075
Toaster	1000	0.2	0.20
Vacuum cleaner	800	0.1	0.08
Video Recorder	300	1	0.30
Washing machine	800	0.2	0.16
Water Heater	Wood only	na	na
Water pump (3/4 hp)	560	5	2.8

Total Rating: 8.42 kW　　　**Total Daily Energy**: 13 kWh

5.3 Water Heating

Water heating is a particularly energy intensive process with a typical hot water cylinder possessing a 4000 W element. It may require between two to six kWh per person per day depending on the number of people in the house and their personal habits. This would make a very considerable difference to the demand assessment above.

It is generally inadvisable to heat water using expensive renewable energy systems. It is better to use systems which use low grade solar energy, such as a solar water heater, or to use a wood burner. When there is an energy excess provided by the more sophisticated systems, it can provide a useful supplement to the water heating.

5.4 Water Pumping With Electricity

It is advisable when using a renewable energy system to pump water to a header tank so that the pump does not need to operate whenever water is required. The pump can also be placed on a timing switch to ensure that it only operates at low periods of power consumption. Doing this ensures that water pumping does not contribute to the peak power loading, only to the average.

A typical household pump delivering 20 litres per minute will consume about 600 W. To calculate the approximate amount of power consumed by the pump the total daily water demand therefore needs to be divided by 20 litres. This figure can be multiplied by 600 W to get an approximate daily power consumption figure.

5.5 Assessing the Water Demand

5.5.1 Domestic Consumption

Table 5.2 can be used to assess household water consumption.

Table 5.2 Average Water Consumption per Usage (L) for Common Household Articles

Shower	90
Bath	120
Kitchen Sink	12
Toilet	10
Automatic washing machine	140
Dishwasher	60
Hand Basin	10
13 mm Garden Hose	15

(Davies Pumps Sales Literature)

In the United Kingdom the average consumption is about 150 litres per person per day. However this figure would includes garden watering and car cleaning etc. Water is similar to electricity in the way in which its consumption increases dramatically as its availability increases and cost falls. A World Health Organisation (WHO) survey in 1970 showed the average water consumption in developing countries ranges from 35 to 90 litres per person per day. Where water is collected from a central point no more than about 200 people should be serviced in this way (Lancashire et al, 1987). Allowance should be made in any demand assessment for future population growth.

5.5.2 Animal Consumption

It is important that animals be provided with the amount of water that they require and at a rate at which they require it if their growth and productivity is not to suffer. Cattle are particularly sensitive to water deprivation whereas sheep have been shown to be able to adapt physiologically (Harrington, 1980).

Table 5.3 Peak Animal Water Consumption Figures (litres per day)

Type of Animal	Litres
Friesen Lactating Dairy Cattle	70
Friesen non Lactating Dairy Cattle	45
Angus Breeding Cow Lactating	56
Angus Breeding Cow non Lactating	40
Jersey Dairy Cattle Lactating	55
Jersey Dairy Cattle non Lactating	35
Rangeland Cattle non Lactating	70
Breeding Ewes	3

(Harrington, 1980)

Harrington (1980) made the following recommendations for determining stock water requirements:

1. with relatively stable stock numbers, the water demand estimate should be based on the numbers held on the property in the January, February, March period,
2. for almost all of the types of grazing animals, with the exception of range cattle, 1/6 of the design daily requirement should be able to be supplied in one hour,
3. designs should be done for the water consumption figures presented in table 5.3.

Lancashire et al (1987) suggested the daily water allowance shown in table 5.4. However, they were writing specifically for the developing country situation where water is often a scarce commodity and therefore, as one might expect, the figures are lower than those above (except for sheep).

Because an animal's water requirement is closely related to its dry matter intake it is relatively simple to extrapolate the above data to other situations to estimate water requirements. In calculating the total requirement, allowance should be made for future population increases in both human and animal populations.

Table 5.4 Animal Daily Water Allowance

Type of Animal	Litres
Horse	50
Cattle	40
Pig	20
Goat	5
Sheep	5
Chicken	0.1

(Lancashire et al, 1987)

5.5.3 Water for Irrigation

The irrigation water requirement is typically highly variable from month to month. Most typical developing country applications have typical water requirements of 20 to 80 m^3 per hectare and pumping heads of 5 to 10 m (Kenna & Gillett, 1985). In New Zealand the transpiration rate, typically designed for in irrigation systems for high value crops such as kiwifruit, is about 4 mm per day. This equates to a volume of 4 litres per m^2 per day or 40,000 litres (40 m^3) per hectare per day.

With irrigation the aim is generally to bring the soil water levels up to field capacity. Any water application beyond this simply drains away. The depth of rooting of the plants and the irrigation rate is also important as any water in the soil profile beyond the reach of roots is effectively useless.

The application rate should not exceed the infiltration rate or else runoff will occur. This is both wasteful, and potentially destructive.

CHAPTER 6

PHOTOVOLTAICS

6.1 Introduction

As discussed in the next section the price of photovoltaic cells, which has long been a barrier to the widespread use of photovoltaic cells, has fallen rapidly over the past years. The current prices make the application of photovoltaic power economic in many remote areas (Lancashire et al, 1987). Future expected improvements in both efficiency and price will make photovoltaic power viable in even more situations.

This chapter begins with a brief look at the price history of photovoltaic cells. It then examines the components of radiation and discusses the difference between the extraterrestrial radiation and the actual incident radiation, and the relationship between the two. It looks at ways of measuring both radiation and sunshine duration. The chapter goes on in section 6.15.2 to look at the use of sunshine hour data to derive a radiation measurement in kWh/m^2 on a horizontal plane. From there it considers how this radiation figure can be used to determine the radiation on an inclined surface.

Having introduced the bulk of the theory it then addresses the issue of design considering the process of array sizing and battery sizing. The author's photovoltaic computer model is then introduced in section 6.15 and a procedure for using the information derived by the model is presented in section 6.16. The chapter ends by validating the results that are generated by the model.

6.2 Photovoltaic Cell Prices

New Zealand lies from latitude 34° to 47° south while the 'solar belt', that region of the world where solar energy is considered to be readily and practically useable, used to be regarded (in 1979) as lying roughly between the latitudes of 40° or 45° north and south (Brothers & Benseman, 1979). The belt has, however, since widened due to the significant price reductions in solar cells over the last 15 years. As shown by the figure 6.1 the price of solar cells in 1990 was a quarter of what it was in 1980.

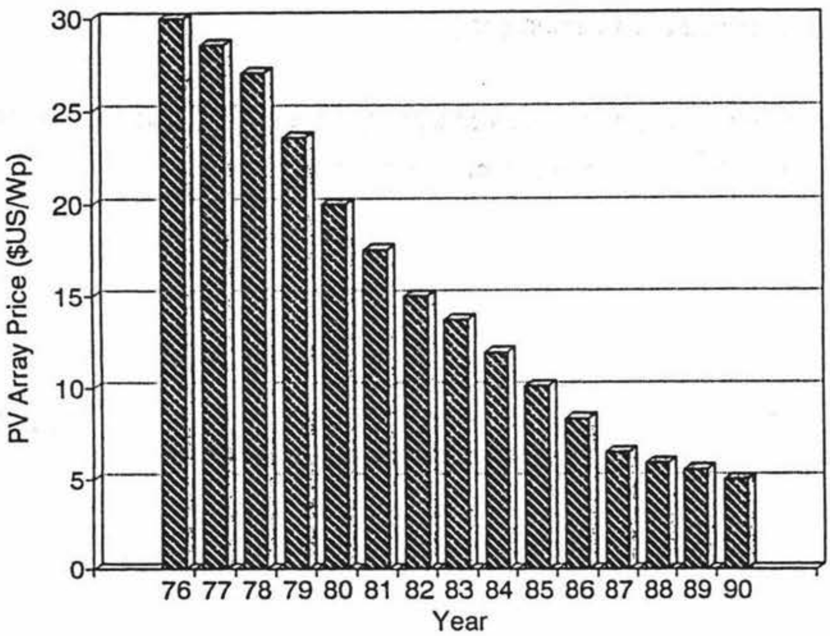

Figure 6.1 Photovoltaic Price History (Derrick et al, 1990)

Due to transport costs the price of photovoltaic cells in New Zealand at the time of writing (April 1992) is less than US$6.00 for only very large orders.

6.3 Components of Radiation

Solar radiation received on the earth's surface is made up of beam and diffuse radiation. Beam radiation is that which is received from the sun without having been scattered by the atmosphere. Diffuse radiation is that component which has had its direction changed due to atmospheric scattering. It includes that which is reflected off the ground. On a heavily overcast day the diffuse radiation may be 100% of the global irradiation.

Global Radiation (generally measured in W/m^2) is the term used to describe the sum of these two components on a horizontal plane while the total solar radiation received over a specific area in a specified time period (generally a day or a month) is called solar irradiation or insolation

(Derrick et al, 1991). This is most commonly expressed in kWh/m^2/day. The more general term of radiation is used in this study.

6.4 Determination of Extraterrestrial Radiation (Ho)

H_o is the amount of radiation which would be received on a horizontal surface (as opposed to one perpendicular to the sun's rays) in the absence of atmosphere or cloud cover.

H_o is found using the following:

$$H_o = \frac{24x3600G_{sc}}{\pi}\left[1+0.033\cos\left(\frac{360n}{365}\right)\right] x \left[\cos\phi\cos\delta\ \sin w_s + \frac{2\pi w_s}{360}\sin\phi\sin\delta\right] \qquad (6.1)$$

where:

n = Julian day of the year

ϕ = Latitude

δ = Declination

W_s = Sunset hour angle in degrees

G_{sc}= 1371 W/m^2

and where W_s is given by:

$$W_s = \cos^{-1}(-\tan\phi\tan\delta) \qquad (6.2)$$

The declination is given by equation 6.3:

$$\delta = 23.45\ \sin\left(360\frac{284+n}{365}\right) \qquad (6.3)$$

The energy from the sun received per unit time, on a unit area of surface perpendicular to the direction of radiation, at the earth's average distance from the sun outside of the earth's atmosphere is called the solar constant, G_{sc} (Duffie & Beckman, 1980). Although Duffie and Beckman (1980) used a value of 1353 W/m^2 it has since been more accurately determined as being 1371 W/m^2 (Appelbaum & Flood, 1990) and so this latter figure has been used within this study.

The declination is the angular position of the sun at solar noon with respect to the plane of the equator where north is positive. It can be calculated for any particular day or for the average day of the month. The average days of the month were used in the analysis and their declination are given in table 6.1. The average days were based on Klein (1977), while the declination figures were derived from equation 6.3 and are consistent with the figures used by Duffie and Beckman (1980).

Table 6.1 Average Days and their Declination

Month	Average Day	Day of Year	Declination
January	17 January	17	-20.9
February	16 February	47	-13.0
March	16 March	75	-2.4
April	15 April	105	9.4
May	15 May	135	18.8
June	11 June	162	23.1
July	17 July	198	21.2
August	16 August	228	13.5
September	15 September	258	2.2
October	15 October	288	-9.6
November	14 November	318	-18.9
December	10 December	344	-23.0

(Average day figures from Klein, 1977)

This method of calculating monthly average extraterrestrial radiation is regarded as the 'standard procedure' (Gopinathan, 1988). It is, however, lengthy and tedious so H_o values have been produced by the author as part of the photovoltaic computer model discussed in section 6.15. These values are presented in table 6.2. The average day of a month is referred to in the sense of the day which experiences a level of extraterrestrial radiation which is closest to the average for the month.

Table 6.2 Monthly Average Extraterrestial Radiation, H_o, kWh/m^2, for $G_{sc} = 1371\ W/m^2$

Latitude	Jan	Feb	March	April	May	June	July	Aug	Sept	Oct	Nov	Dec
60.0	1.0	2.4	4.7	7.7	10.2	11.4	10.8	8.6	5.7	3.0	1.3	0.6
57.5	1.3	2.8	5.1	7.9	10.3	11.5	10.9	8.9	6.1	3.5	1.7	1.0
55.0	1.7	3.2	5.5	8.2	10.5	11.5	11.0	9.1	6.5	3.9	2.1	1.3
52.5	2.1	3.7	5.9	8.5	10.6	11.5	11.1	9.3	6.8	4.3	2.5	1.7
50.0	2.5	4.1	6.3	8.8	10.7	11.6	11.1	9.5	7.2	4.7	2.9	2.1
47.5	3.0	4.5	6.6	9.0	10.8	11.6	11.2	9.7	7.5	5.1	3.3	2.6
45.0	3.4	4.9	7.0	9.2	10.9	11.6	11.3	9.9	7.8	5.5	3.7	3.0
42.5	3.8	5.3	7.3	9.5	11.0	11.6	11.3	10.0	8.1	5.9	4.2	3.4
40.0	4.2	5.7	7.6	9.6	11.1	11.6	11.3	10.2	8.4	6.3	4.6	3.8
37.5	4.7	6.1	8.0	9.8	11.1	11.6	11.3	10.3	8.6	6.6	5.0	4.3
35.0	5.1	6.5	8.3	10.0	11.1	11.6	11.3	10.4	8.9	7.0	5.4	4.7
32.5	5.5	6.9	8.5	10.1	11.1	11.5	11.3	10.5	9.1	7.3	5.8	5.1
30.0	5.9	7.2	8.8	10.3	11.1	11.5	11.3	10.6	9.3	7.7	6.2	5.5
27.5	6.3	7.6	9.0	10.4	11.1	11.4	11.2	10.6	9.5	8.0	6.6	6.0
25.0	6.7	7.9	9.3	10.4	11.1	11.3	11.1	10.7	9.7	8.3	7.0	6.4
22.5	7.1	8.2	9.5	10.5	11.0	11.2	11.1	10.7	9.8	8.6	7.4	6.8
20.0	7.5	8.6	9.7	10.6	10.9	11.0	10.9	10.7	10.0	8.9	7.7	7.2
17.5	7.9	8.8	9.9	10.6	10.9	10.9	10.8	10.6	10.1	9.1	8.1	7.6
15.0	8.2	9.1	10.0	10.6	10.7	10.7	10.7	10.6	10.2	9.3	8.4	7.9
12.5	8.6	9.4	10.2	10.6	10.6	10.5	10.5	10.5	10.3	9.6	8.7	8.3
10.0	8.9	9.6	10.3	10.6	10.5	10.3	10.3	10.5	10.3	9.8	9.1	8.7
7.5	9.2	9.9	10.4	10.5	10.3	10.1	10.1	10.4	10.4	10.0	9.3	9.0
5.0	9.5	10.1	10.5	10.4	10.1	9.9	9.9	10.2	10.4	10.1	9.6	9.3
2.5	9.8	10.3	10.5	10.4	9.9	9.6	9.7	10.1	10.4	10.3	9.9	9.6
0.0	10.1	10.4	10.6	10.3	9.7	9.3	9.5	9.9	10.4	10.4	10.1	9.9
-2.5	10.3	10.6	10.6	10.1	9.5	9.1	9.2	9.8	10.3	10.5	10.4	10.2
-5	10.6	10.7	10.6	10.0	9.2	8.8	8.9	9.6	10.3	10.6	10.6	10.5
-7.5	10.8	10.8	10.6	9.8	8.9	8.5	8.6	9.4	10.2	10.7	10.8	10.7
-10	11.0	10.9	10.5	9.6	8.7	8.1	8.3	9.2	10.1	10.7	10.9	11.0
-12.5	11.2	11.0	10.5	9.4	8.4	7.8	8.0	8.9	10.0	10.8	11.1	11.2
-15	11.4	11.1	10.4	9.2	8.1	7.5	7.7	6.7	9.9	10.8	11.2	11.4
-17.5	11.5	11.1	10.3	9.0	7.7	7.1	7.4	8.4	9.7	10.8	11.4	11.6
-20	11.6	11.1	10.2	8.7	7.4	6.7	7.0	8.1	9.5	10.7	11.5	11.7
-22.5	11.8	11.1	10.0	8.5	7.1	6.4	6.6	7.8	9.3	10.7	11.5	11.9
-25	11.9	11.1	9.9	8.2	6.7	6.0	6.3	7.5	9.1	10.6	11.6	12.0
-27.5	11.9	11.1	9.7	7.9	6.3	5.6	5.9	7.2	8.9	10.5	11.7	12.1
-30	12.0	11.0	9.5	7.6	6.0	5.2	5.5	6.8	8.7	10.4	11.7	12.2
-32.5	12.0	10.9	9.3	7.3	5.6	4.8	5.1	6.5	8.4	10.3	11.7	12.3
-35	12.0	10.8	9.1	6.9	5.2	4.4	4.7	6.1	8.1	10.2	11.7	12.3
-37.5	12.0	10.7	8.8	6.6	4.8	4.0	4.3	5.7	7.8	10.0	11.6	12.3
-40	12.0	10.6	8.5	6.2	4.4	3.6	3.9	5.4	7.5	9.8	11.6	12.4
-42.5	12.0	10.4	8.3	5.8	4.0	3.2	3.5	5.0	7.2	9.6	11.5	12.4
-45	11.9	10.2	8.0	5.5	3.6	2.8	3.1	4.6	6.9	9.4	11.4	12.4
-47.5	11.9	10.1	7.7	5.1	3.2	2.4	2.7	4.2	6.5	9.2	11.4	12.3
-50	11.8	9.9	7.3	4.7	2.8	2.0	2.3	3.8	6.2	8.9	11.2	12.3
-52.5	11.7	9.6	7.0	4.3	2.4	1.6	1.9	3.4	5.8	8.7	11.1	12.3
-55	11.6	9.4	6.6	3.9	2.0	1.3	1.6	3.0	5.4	8.4	11.0	12.2
-57.5	11.5	9.2	6.3	3.4	1.6	0.9	1.2	2.6	5.1	8.1	10.9	12.2
-60	11.4	8.9	5.9	3.0	1.2	0.6	0.9	2.2	4.7	7.8	10.7	12.1

6.5 Actual Incident Radiation (H)

The previous section demonstrated how the amount of radiation falling on a horizontal plane in a particular location, assuming no effect of atmosphere or cloud, (H_o), can be calculated entirely in the absence of any sort of meterological data. Light reaching the earth is, however, influenced very significantly by both atmosphere and cloud. The two main effects are atmospheric scattering by air molecules, water vapour and dust, and atmospheric absorbtion by O_3, H_2O, and CO_2 (Duffie & Beckman, 1980). The relationship between H_o and H is given by the clearness index, dealt with in section 6.7.

Global radiation on a clear day in the tropics can exceed 1000 W/m^2, while in northern Europe it may fall to less than 100 W/m^2 on a cloudy day (Derrick et al, 1991). For the purposes of design of photovoltaic (PV) systems it is more important to know the total solar energy received over a day or month per unit area. For a horizontal surface this is denoted H. This is typically 5 to 7 kWh per square metre per day in the tropics but can be less than 0.5 kWh per square metre per day on a winter's day in northern Europe (Derrick et al, 1991). At the peak of summer in New Zealand the average daily global radiation is typically around 470 W/m^2 while a typical summer H value is around 6 kWh/m^2/day.

6.6 Measuring Solar Radiation

Because the output of a photovoltaic cell is directly proportional to the temperature of the cell and to the amount of radiation it receives[10], it is very important that a careful assessment is made of the solar radiation levels available in relation to the energy requirement. These levels will vary during the day depending on the angle of the sun, the season, the latitude and the climate (Derrick et al, 1991). One way of assessing the actual radiation received on a site is to install a device to measure it directly.

6.6.1 Instruments for Measuring Solar Radiation

Instruments for measuring solar radiation come in two basic types:

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[10]While the wavelength of the light does have an effect it is not significant enough to be of practical interest.

Pyrheliometer: This measures the solar radiation from the sun and from a small portion of the sky around the sun.

Pyranometer: This measures the total solar radiation on a horizontal surface (beam plus diffuse).

These two types of devices provide results in a form which is able to be used directly in the assessment of photovoltaic cell output. It is from these instruments that most data on solar radiation is obtained (Duffie & Beckman, 1980).

Some of both types of instruments operate by producing a voltage from thermopile detectors which is a function of the incident radiation. Others utilise bimetallic elements which respond differently to temperature changes. The amount of movement is a function of the radiation induced heating of the elements.

6.6.2 Instruments for Measuring Duration of Sunshine

At many meteorological stations it is sunshine duration which is recorded, as opposed to the total radiation. The following two instruments are in common use by weather stations for the determination of this parameter:

Campbell-Stokes Sunshine Recorder: This uses a solid glass sphere to burn a mark on a strip of paper whenever the beam radiation is above a certain critical level.

Foster Sunshine Switch: This is based on the output of two photovoltaic cells, one of which is exposed to beam radiation and the other shaded from it. The difference in the output of these two cells provides a measure of the duration of sunshine.

Both of these instruments are expensive and so are rarely used to assess the solar radiation at a particular site being considered for a remote area power supply.

6.7 Clearness Index

A 'clearness index', K, has been developed to enable comparisons to be made between different sites. K can be expressed as shown in equation 6.4.

$$K = \frac{H}{H_o} \tag{6.4}$$

H_o and H must be expressed in the same units, kWh/m^2 in this study. In practice K would not be expected to exceed 0.8 and on a particularly dull day may fall as low as 0.1 (Western, 1990). The K value is also useful as it, in turn, provides a relationship between diffuse and global radiation which is required for calculating the solar radiation on an inclined surface (Benseman & Cook, 1969). This might be expected as it is obvious that on cloudy days the amount of diffuse radiation is high while under clear sky conditions it is significantly less. Figure 6.4 shows the correlation for New Zealand data.

6.8 Use of Sunshine Hour Data to Derive Radiation on a Horizontal Plane

Where sunshine hour data is available, equation 6.5 may be used to calculate the average amount of radiation actually received on a horizontal surface (after Gopinathon, 1988). According to Gopinathan (1988), this procedure for estimating H on the basis of sunshine hours is applicable to any location in any part of the world and results in an accuracy of about 10%. However, as can be seen from section 6.15.3, for most New Zealand locations it results in a greater accuracy.

$$\frac{H}{H_o} = a + b\left(\frac{S}{S_o}\right) \tag{6.5}$$

where a and b are constants derived using the following equation:

$$a = -.309 + .539\cos\phi - .0693h + .290\left(\frac{S}{S_o}\right) \tag{6.6}$$

$$b = 1.527 - 1.027\cos\phi + .0926h - .359\left(\frac{S}{S_o}\right) \tag{6.7}$$

and where:

ϕ = Latitude in degrees (south is negative)
h = Height above sea level in km

H = Monthly average daily global radiation on a horizontal surface

H_o = Monthly average daily extraterrestrial radiation on a horizontal surface

S = Monthly average daily sunshine duration in hours

S_o = Monthly maximum possible daily sunshine duration in hours

S_o can be derived from meterological data, from figure 6.2, or from equation 6.8.

$$S_o = \frac{2}{15}\cos^{-1}(-\tan\phi\tan\delta) \tag{6.8}$$

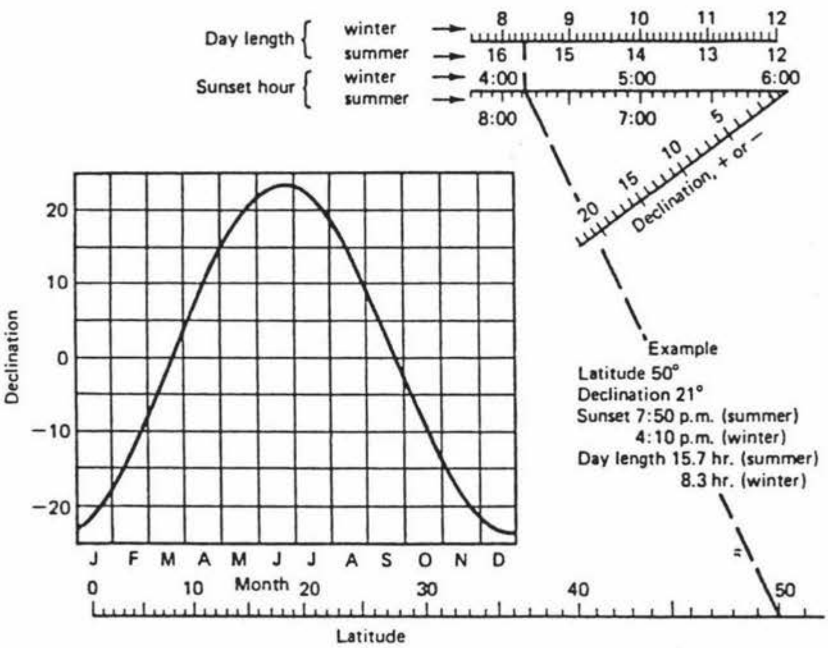


Figure 6.2 Nomogram to Determine Time of Sunset and Sunrise (Duffie & Beckman, 1980)

6.9 Determining the Amount of Radiation on an Inclined Plane

The previous section enables the actual average radiation falling on a horizontal surface to be derived. Normally, however, the photovoltaic array will be mounted at some angle to the horizon so that more light is intercepted. Therefore, being able to assess the amount of solar radiation incident on a tilt plane is very important. The lower the sun remains during the day the more advantage there is to be gained by tilting the array towards the equator (north for all southern hemisphere locations).

To capture the maximum amount of energy over a period of a year the optimum tilt angle is that equal to the latitude (Gopinathon, 1990). However, it is often convenient to alter the tilt of the array once or twice during the year. In this case the optimum tilt angle for summer is the absolute value of the latitude minus 10°, while in winter it is the absolute value of the latitude plus 20° (the absolute value simply means taking the value as positive for both latitudes).

If one is prepared to alter the angle even more frequently, figure 6.3 can be used to determine the optimum angle for a southern hemisphere location. The optimum frequency of altering the angle will depend on the demand pattern over the year and the degree of tolerance built into a design. A minimum tilt angle of 15° should be maintained at all times to ensure water runoff.

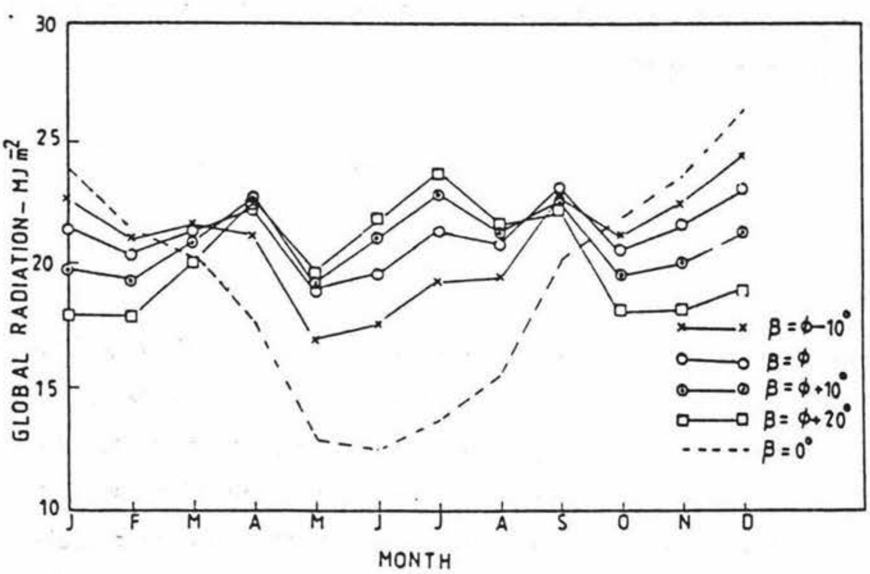


Figure 6.3 Annual Variation of Global Radiation on Horizontal and Tilted Surface for Qacha's Nek, South Africa (Gopinathon, 1990)

It is important that the influence of tilting on the amount of radiation received can be determined. To do this a model is required for converting the horizontal radiation to that on an inclined surface. This is termed a translation model. Translation models are based on the fact that the relationship between a plane of any particular orientation relative to the earth and the incoming solar radiation can be described in terms of the following angles:

ϕ = Latitude, where north is positive

δ = Declination

β = Slope of the plane

Y = Surface azimuth angle (where 0 is due south, east positive, west negative)

W = Hour angle

Θ = Angle of incidence

(Duffie & Beckman, 1980)

6.10 Types of Translation Models and their Characteristics

Translation models are developed to calculate the amount of energy available on any surface tilted at any angle and facing a given direction (Chowdhury & Rahman, 1987). The available models can be divided into two main categories:

1. isotropic models which assume that the diffuse and reflected components are uniformly distributed over the sky,
2. anistropic models which do not make such an assumption.

Available models include those by Luis and Jordan, Hay, Klucher, Heywood, Norris, and Klein. The only significant difference between the models appears in their assessment of the sky diffuse component. Hay's model assumes that diffuse radiation on a horizontal surface is composed of a circumsolar component as coming from the sun's direction and an isotropically distributed diffuse component coming from the rest of the skydome (Ma & Iqbal, 1983). The Hay model is an anistropic model. However, when the diffuse component approaches the global value, the Hay model reduces to the isotropic model.

The models proposed by Lui and Jordan, and Hay are supposed to be applicable to situations anywhere in the world (Gopinathan, 1990). Ideally models ought to treat the direct and diffuse components separately but measurements of both the direct and diffuse components are very rarely available. Therefore it is generally only the global horizontal radiation used in the various estimation models to estimate the diffuse component.

6.10.1 Equations Forming the Basis of the Models

The total amount of radiation received by an inclined surfaces, H_T, is given by the following:

$$H_T = H_B + H_S + H_R \tag{6.9}$$

where:

$$H_R = H_\rho (1-\cos\beta)/2 \tag{6.10}$$

and where ρ is the ground reflection coefficient. Where no other information is available it is common to use a value of ρ = 0.2 (Gopinathon, 1990). Typical values of reflectivity range from 0.03 to 0.25 for fields and normal surroundings. Snow can have a value up to 0.87 (Benseman & Cook, 1969).

The value of the beam component, H_b, is given by:

$$H_B = (H - H_d)\, R_b \tag{6.11}$$

where R_b, the ratio of extraterrestial radiation on an inclined surface to that on a horizontal, is given by the following:

$$R_b = \frac{\cos(\phi+\beta)\cos\delta\sin W_s^1 + \left(\frac{\pi}{180}\right) W_s^1 \sin(\phi+\beta)\sin\delta}{\cos\phi\cos\delta\sin W_s + \left(\frac{\pi}{180}\right) W_s \sin\phi\sin\delta} \tag{6.12}$$

and where W_s^1 is given by the lesser of:

$$W_s^1 = \min \begin{bmatrix} \cos^{-1}(-\tan\phi\tan\delta) \\ \cos^{-1}(-\tan(\phi+\beta)\tan\delta \end{bmatrix} \tag{6.13}$$

(for surfaces sloped towards the equator)

Care must be taken to distinguish W_s from $W_s^1 W_s$ is the sunset hour angle for a horizontal plane whereas $W_s^1$is the sunset hour angle for the tilted surface for the average day of the month. The Hay Model can then be used to calculate Hs, the sky diffuse radiation using equation 6.14. The

$$H_s = H_d\,([(H-H_d)/H_o]\,R_b + [(1-\cos\beta)/2] \\ x[1-(H-H_d)H_o]) \tag{6.14}$$

Lui and Jordan model is considerably simpler and often no less accurate than the Hay model. Often it is favoured when calculations are not able to be performed with a computer. The Lui Jordan assessment of H_s is given in equation 6.15.

$$H_s = H_d(1+\cos\beta)/2 \tag{6.15}$$

The clearness index assessed earlier can be used to derive H_d, the daily diffuse radiation on a horizontal surface, as shown below (after Duffie & Beckman, 1980). H_d is required in equations 6.14 or 6.15 to derive Hs.

$$\frac{H_d}{H} = .775 + 0.00653(w_s-90) - [0.505 + 0.00455 \\ (w_s - 90]\cos[115K_T - 103] \tag{6.16}$$

where K_T is the monthly average clearness index.

A correlation between the proportion of the global radiation which is diffuse, and the clearness index, K, has also been developed by Western (1990). This is shown in figure 6.4. It would appear that in New Zealand the sky diffuse radiation component of global radiation is considerably lower than in the USA, particularly in summer (Western 1990). This may be explained by the higher levels of air pollution resulting in a greater degree of refraction and so in a higher component of diffuse radiation. Some differences may also be attributable to instrumental problems such as shading ring corrections (Duffie & Beckman, 1980), and variations between pryanometers used (Lui & Jordan, 1960).

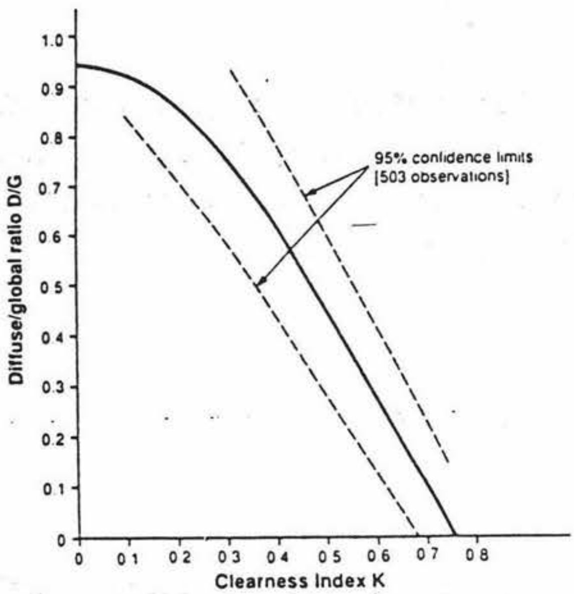


Figure 6.4 Daily Diffuse/Global Ratio as a Function of the Clearness Index for Wellington and Gracefield, New Zealand (Western, 1990)

By combining equations 6.10, 6.11, and 6.14, the total solar radiation on any inclined surface is able to be calculated.

6.11 Overview of Solar Design

Suppliers of photovoltaic systems have data on solar resources throughout the world and will often calculate the size of the photovoltaic array required. It may still, on occasions, be necessary to do it independently. To do this it is necessary to know both the demand and the levels of solar radiation throughout the year. This is usually specified in terms of average daily radiation for each month although some photovoltaic applications will require the knowledge of daily or even hourly radiation figures (Chowdury & Rahman, 1987).

The DC power produced from photovoltaic systems can be directly used to power lights, universal motors and other resistive loads. To produce AC power from a DC solar cell an inverter is placed in the circuit before the load. Inverters should be carefully chosen to closely match the power demand of the load. A wave form which resembles a sine wave is produced with different degrees of distortion depending on the type and cost of inverter chosen (Charters, 1986).

Most systems employ a voltage regulator to protect the battery from over voltage conditions. This is connected between the battery and the photovoltaic array and simply dissipates any excess energy. A photovoltaic circuit also includes a blocking diode between the array and the battery to prevent current flowing out of the battery to the array during the night.

6.12 Sizing the Photovoltaic Array

6.12.1 Rating Photovoltaic Arrays

Arrays vary in their efficiency and so, for comparative purposes, are rated in units of 'peak watts', Wp. The peak watt rating of an array describes its output at a radiation level of 1,000 W/m^2 at a temperature of 25°C. Two arrays may therefore have exactly the same peak watt rating and yet have different areas because of their different efficiencies.

Example: Suppose that on a 'typical' day during January in New Zealand the amount of radiation received on an array's surface is 24.6 MJ/m^2 per day. Because one watt-hour equates to 3,600 Joules (1 kWh/m^2 = 3.6 MJ/m^2), this is equal to 24.6/3.6 = 6.83 kWh/m^2 per day.

If the array is rated at 150 Wp then it will produce:

(6.83 x 1,000) /1,000 x 150 = 1025 Wh or 1.02 kWh per day under the specified radiation levels.

A similar calculation may be done where only the array area and the efficiency is known.

Example: Suppose that an array has an area of 5 m^2 and is known to be 12% efficient. Under the above radiation conditions the array output will be:

6.83 kWh/m^2 x 5m^2 x 12% = 4.1 kWh per day.

To express an array whose area and efficiency is known in terms of a peak watt rating equation 6.17 may be used:

$$Array\,Wp = Area\,(m^2) \times 1000 \times array\ efficiency \tag{6.17}$$

Alternatively, to convert array Wp rating and efficiency into an area equation 6.18 may be used:

$$Array\ area\,(m^2) = \frac{Wp \times \frac{1}{array\ efficiency}}{1000} \tag{6.18}$$

The array rating required for a given situation may be roughly estimated by equation 6.19.

$$Array\ Required\,(Wp) = \frac{Demand}{Insolation} \times 1000 \tag{6.19}$$

Table 6.3 is based on a 10% efficient array, an average ambient temperature of 25°C and a 100% efficient subsystem which was derived by the author using equation 6.19. This should not be used to make anything other than a very rough assessment.

Table 6.3 Array Size Required Based on 10% Efficient Array

		Average Daily Power Demand for Month (kWh/m2)									
		0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
	1.0	100	200	300	400	500	600	700	800	900	1000
	1.5	67	133	200	267	333	400	467	533	600	667
	2.0	50	100	150	200	250	300	350	400	450	500
	2.5	40	80	120	160	200	240	280	320	360	400
	3.0	33	67	100	133	167	200	233	267	300	333
Average Daily Radiation for Month (kWh/m2)	3.5	29	57	86	114	143	171	200	229	257	286
	4.0	25	50	75	100	125	150	175	200	225	250
	4.5	22	44	67	89	111	133	156	178	200	222
	5.0	20	40	60	80	100	120	140	160	180	200
	5.5	18	36	55	73	91	109	127	145	164	182
	6.0	17	33	50	67	83	100	117	133	150	167
	6.5	15	31	46	62	77	92	108	123	138	154
	7.0	14	29	43	57	71	86	100	114	129	143
	7.5	13	27	40	53	67	80	93	107	120	133
	8.0	13	25	38	50	63	75	88	100	113	125
	8.5	12	24	35	47	59	71	82	94	106	118

6.12.2 Array Sizing Temperature Correction

The efficiency of solar cells drops off at higher temperatures. This is because higher temperatures cause an increase in the resistance of solar cells (Teoh et al, 1987). It is therefore desirable to operate solar cells at as low a temperature as practical. The Wp rating of most solar cells is determined at 25°C. A power drop of about 0.4% is experienced for every 1°C temperature rise (Charters, 1986).

6.13 Determining Battery Size Requirement

Batteries are required in almost all photovoltaic applications with the exception of water pumping (Starr et al, 1983). The output of a solar panel is well suited to battery charging as it is the current rather than the voltage which varies with radiation intensity (Charters, 1986).

There are two common methods for determining the storage requirement. The first is to consider the maximum number of days or hours the battery might be required to meet the load independently, and the likely load over this period. The second is to base the amount of battery capacity on the loss of load probability (LOLP). The LOLP describes the confidence level at which the sized system will be able to satisfy the load. It was this second method that the author used to generate the design tables in Appendix F.

The peak power requirement needs to be checked, along with the maximum depth of discharge to ensure that there is sufficient time between the negligible sunshine periods to charge the battery bank up to its rated capacity. Typical battery capacities for equatorial regions have a three to five day storage capacity for low status loads such as lighting, and five to ten days for loads requiring a very low LOLP (Derrick et al, 1990).

The chosen battery bank must meet the following criteria:

1. daily discharge depth should not exceed 10% of the batteries ampere hour capacity at the rate proposed,
2. under worst conditions the battery should not be discharged beyond 50% of its ampere hour capacity at the rate proposed

(Exide Battery Manual).

For maximum life the battery voltage per cell may not be allowed to fall below the minimum voltage specified per cell in the manufacturer's data. If this happens at any time then the load must be immediately disconnected and the batteries allowed to recharge. A generator may be used to speed the recharging process.

6.13.1 Temperature Correction

All battery discharge performance data is based on 25°C. A correction should be made if the ambient temperature is consistently below 20°C. Table 6.4 shown below is a typical correction table but manufacturer's data should preferably be consulted. The ampere hour capacity required at 25°C divided by the correction factor applicable to the lower operating temperature gives the required ampere hour capacity at that temperature.

Table 6.4 Temperature Correction Data

Temperature Correction Factors						
Discharge Rate Hours	To be applied to 25°C Data at					
	0°C	5°C	10°C	15°C	20°C	25°
0.2	0.55	0.64	0.73	0.82	0.91	1
1.0	0.60	0.68	0.76	0.84	0.92	1
3.0	0.65	0.72	0.79	0.86	0.93	1
10.0	0.70	0.76	0.82	0.88	0.94	1

(Exide Battery Manual)

The amount of battery storage required consists of two components, the long term component and the short term component. The first is the amount of energy needed to satisfy the demand during the cloudy days of the month. The second is the peak demand beyond the daily output of the array.

6.14 Photovoltaic Pumping

Solar pumps are most cost effective for applications with power requirements in the order of a few hundred watts. The main components of a photovoltaic pumping system are essentially the array, motor, pump, and a storage and distribution system.

Generally, permanent magnet DC motors are used with photovoltaic pumping systems. This is because the array supplies a DC current, they are reliable, are reasonably low cost and they are able to operate over a wide range of input voltages (Pulfrey et al, 1987). Inverters may, however, be used to convert the DC to AC for large applications. The motor's operating characteristics should be matched to that of the pump by choosing the appropriate gear ratio. Additional smoothing can be provided by the use of a flywheel (Kenna & Gillett, 1985).

6.15 Introduction to the Photovoltaic Computer Model

A photovoltaic computer model has been created by the author. Drawing on the theory and equations presented earlier in this chapter it enables the following to be calculated:

1. The extraterrestrial radiation (Ho, kWh/m^2) for any site in the southern hemisphere based on the month and the latitude.

2. The average amount of radiation, (H, kWh/m^2), incident during a particular month, based on sunshine hour data.

3. The average monthly radiation falling onto a plane, (HT, kWh/m^2), tilted towards the equator. This is based on H, the latitude and the angle of tilt. To do this the Hay model is used as described in section 6.8. The Hay model was chosen as it is applicable to anywhere in the world.

4. H_T is then be used to size the optimum combination photovoltaic array and battery to meet any given load with a 1% LOLP based on the relative cost of these two components, for any location in the southern hemisphere.

Each of these features of the computer model has been used by the author to generate tables which are included either in the body or in an Appendix of this study.

6.15.1 Extraterrestrial Radiation

Equations 6.1, 6.2 and 6.3 were used to produce H_o results for every combination of month to the nearest 2.5° latitude. This information is produced in the table 6.2. Section 6.15.1 examines the validation of these results.

6.15.2 Determination of Radiation on a Horizontal Surface, H, Based on Sunshine Hours

The technique of using sunshine hours to derive H described in section 6.6 was applied to all of the sites in New Zealand for which long term sunshine and radiation data is available. Regional constants were developed by the author through trial and error. These regional constants were used as a multiplier of the 'a' value shown in equation 6.6. This significantly improved the accuracy of solar radiation predicted from sunshine hours as discussed in section 6.17.3.

The results of applying this technique are presented in tables in Appendix C. They enable a comparison to be made between actual measured radiation data and that calculated using sunshine duration information, with and without the application of regional constants. The tables show So, the maximum possible number of sunshine hours; S, the average number of sunshine hours received; and Hm, the actual measured radiation. The value calculated from the sunshine hours, Hc, is given, as is Hc(adj), the value calculated from the sunshine hours and using the regional constants.

By applying the regional constant nearest to an area under consideration, sunshine hours may be used to assess H more accurately. The regional constants are shown in table 6.5.

Table 6.5 Grid References and Regional Coefficients of Selected New Zealand Locations

Location	Latitude	Longitude	Height (m)	Regional Coefficient
Alexandra	45 16S	169 23E	141	1.13
Auckland AP	37 01S	174 48E	8	1.00
Christchurch AP	43 29S	172 32E	30	1.00
Dunedin AP	45 56S	170 12E	1	1.00
Gisborne AP	38 40S	177 59E	4	0.81
Hokitika	42 43S	170 59E	39	0.88
Invercargill	46 25S	168 20E	0	1.35
Kaikoura	42 25S	173 42E	108	0.94
Kaitai	35 04S	173 17E	80	0.93
Kelburn	41 17S	174 46E	125	0.91
Leigh	36 16S	174 48E	27	1.03
Levin	40 39S	175 16E	46	1.13
Mt.John	43 59S	170 28E	1027	1.07
Nelson AP	41 17S	173 14E	2	0.82
Ohakea	40 12S	175 23E	48	1.00
Rukuhia	37 50S	175 18E	66	1.02
Whenuapai	36 47S	174 38E	26	1.04

In many areas only sunshine hour data is available, so a series of tables have been developed by the author using the method shown in section 6.6. This method enables the radiation on a horizontal surface to be determined on the basis of sunshine hours and latitude. These tables are presented in Appendix B, and are for an average of three to eight sunshine hours per day and for latitudes from 0 to 60° south. Where the precise number of sunshine hours is not covered by the tables they may be interpolated between. The accuracy of these tables is discussed in section 6.17.3. Appendix D presents a summary of measured daily radiation values for locations in New Zealand.

6.15.3 Assessment of the Total Amount of Radiation on an Inclined Surface (H_T)

The technique described in section 6.7 has been used by the author to derive a series of design tables covering the latitude of New Zealand for the common tilt angles. These tables, shown in Appendix E, enable the radiation on a tilted surface to be determined using only the inputs of tilt angle, latitude and radiation on a horizontal surface. They cover the latitude of New Zealand and all of the common tilt angles.

In the determination of H_d on the basis of the clearness index, K, the correlation developed by Western (1990), shown in figure 6.4, was used. It was thought that this correlation would be more accurate for New Zealand conditions because it was New Zealand data used to determine the correlation. The accuracy of the author's computer model generated results is shown by a comparison to actual measured results in tables 6.6 and 6.7. This is discussed in section 6.15.2.

6.15.4 Sizing the Photovoltaic Array and Battery

A method devised by Groumpos and Papageorgiou (1987) enables the sizing of both the solar array and the battery. Cost data is entered which enables the minimum cost system to be selected.

The array size (A) is calculated using the following equation for each month:

$$A = \frac{DL}{[\eta\, I(1 - M x R)]} \qquad (6.20)$$

where:

DL (kWh/day) is the estimated daily demand for the month

η is the system efficiency

I is the average radiation (kWh/m^2) for the month

R is the ratio of the standard deviation in daily radiation over the average daily radiation
M is the balancing parameter between the array and the battery

The optimum M is given by the following:

$$M_{opt} = \frac{-T+(T^2+4ZW)^{1/2}}{2Z} \tag{6.21}$$

where:

$W = (CF)(BC)C\eta I$

$T = 2(CF)(BC)C\eta IR$

$Z = (AC)R-(CF)(BC)C\eta IR^2$

and where:

AC is the effective array cost per m^2

BC is the effective battery cost per kWh of storage capacity

R is the standard deviation of the daily radiation received over the month divided by the average daily radiation for the month

C is the number of consecutive days that the battery should be able to supply the load, given by:

$$C = \frac{CA}{M} + CB \tag{6.22}$$

Ca and Cb are dependant on R. Their values are determined as follows:

For any value of R between 0.1 and 0.3

$Ca = 2.35R + 0.465$

$Cb = 1.3R - 1.06$

For values of R between 0.3 and 1.0

$Ca = 3.8371R + 0.0189$

$Cb = 0.8486R - 0.9246$

Table 6.6 Measured and Calculated Global Radiation on an Inclined Surface.

Slope = Latitude - 10 degrees
= 19.32 degrees

	Slope = 0			Gopinathon					Author's computer model				
Month	H	Hd	Measured Ht	Rb	L&J	e	Hay	e	Rb	L&J	e	Hay	e
Jan	7.2	2.2	6.9	0.93	6.9	0.2	6.8	0.3	0.92	6.8	0.5	6.8	1.2
Feb	6.9	2.0	6.8	0.99	6.8	0.1	6.8	0.1	0.99	6.8	0.1	6.8	0.4
Mar	5.8	1.7	6.3	1.10	6.2	0.5	6.3	1.0	1.10	6.2	0.5	6.3	1.1
Apr	4.7	1.4	5.6	1.25	5.5	1.3	5.7	1.7	1.25	5.5	1.1	5.7	1.9
May	3.9	1.0	5.2	1.41	5.1	1.9	5.3	2.3	1.41	5.1	1.7	5.3	2.5
Jun	3.4	0.9	4.7	1.51	4.7	0.7	4.9	4.3	1.51	4.7	0.8	4.9	4.1
Jul	3.7	0.9	5.3	1.46	5.0	5.3	5.3	1.0	1.46	5.0	5.1	5.3	0.8
Aug	4.7	1.1	5.8	1.32	5.8	1.2	6.0	4.6	1.32	5.8	1.0	6.0	4.3
Sept	5.9	1.3	6.6	1.16	6.6	1.2	6.8	3.1	1.16	6.6	0.9	6.7	2.9
Oct	6.4	1.9	6.6	1.03	6.5	1.9	6.5	1.1	1.03	6.5	2.2	6.5	1.5
Nov	7.1	2.1	6.7	0.94	6.8	0.9	6.7	0.4	0.94	6.8	0.7	6.7	0.2
Dec	7.6	2.1	7.2	0.91	7.1	0.8	7.1	1.6	0.90	7.1	1.4	7.0	2.4
					MPE =	1.3	MPE =	1.8		MPE =	1.3	MPE =	1.9

H = actual radiation on horizontal
Hd = diffuse component of that radiation
Ht = radiation on an inclined plane
(All radiation values expressed in kWh/m2)

L&J = Lui and Jordan model assessment of Ht
Hay = Hay model assessment of Ht
MPE = mean percentage error

Table 6.7 Measured and Calculated Global Radiation on an Inclined Surface.

	Slope = 0			Slope = Latitude (29.32 degrees)									
				Gopinathon					Author's computer model				
Month	H	Hd	Measured Ht	Rb	L&J	e	Hay	e	Rb	L&J	e	Hay	e
Jan	7.2	2.2	6.6	0.86	6.5	2.3	6.4	3.4	0.84	6.4	3.6	6.3	4.9
Feb	6.9	2.0	6.5	0.95	6.6	1.7	6.6	1.9	0.95	6.6	1.4	6.6	1.6
Mar	5.8	1.7	6.1	1.11	6.2	2.7	6.4	4.9	1.11	6.2	2.4	6.3	4.5
Apr	4.7	1.4	5.8	1.33	5.8	1.0	6.0	3.1	1.33	5.8	1.0	6.0	3.1
May	3.9	1.0	5.8	1.57	5.5	4.0	5.9	1.4	1.57	5.5	4.1	5.9	1.2
Jun	3.4	0.9	5.4	1.71	5.2	3.7	5.6	2.5	1.71	5.2	3.9	5.5	2.2
Jul	3.7	0.9	5.6	1.64	5.5	0.5	5.9	5.3	1.64	5.5	0.4	5.9	5.3
Aug	4.7	1.1	6.7	1.43	6.2	6.6	6.5	2.4	1.42	6.2	6.9	6.5	2.8
Sept	5.9	1.3	6.7	1.19	6.8	0.8	6.9	3.5	1.19	6.8	0.6	6.9	3.2
Oct	6.4	1.9	6.2	1.00	6.3	1.2	6.4	2.1	0.99	6.3	0.8	6.3	1.6
Nov	7.1	2.1	6.5	0.88	6.4	0.9	6.4	1.7	0.87	6.4	1.8	6.3	2.7
Dec	7.6	2.1	6.7	0.83	6.6	0.5	6.5	2.0	0.82	6.6	1.6	6.5	3.3
					MPE =	2.2	MPE =	2.8		MPE =	2.4	MPE =	3.0

H = actual radiation on horizontal
Hd = diffuse component of that radiation
Ht = radiation on an inclined plane
(All radiation values expressed in kWh/m2)

L&J = Lui and Jordan model assessment of Ht
Hay = Hay model assessment of Ht
MPE = mean percentage error

CF is a factor which depends on the allowable depth of discharge and equals

$$CF = \frac{1}{(DOD)_{max}\eta_b} \tag{6.23}$$

and where:

η_b = Overall Battery Efficiency

DOD is the maximum permissible depth of discharge

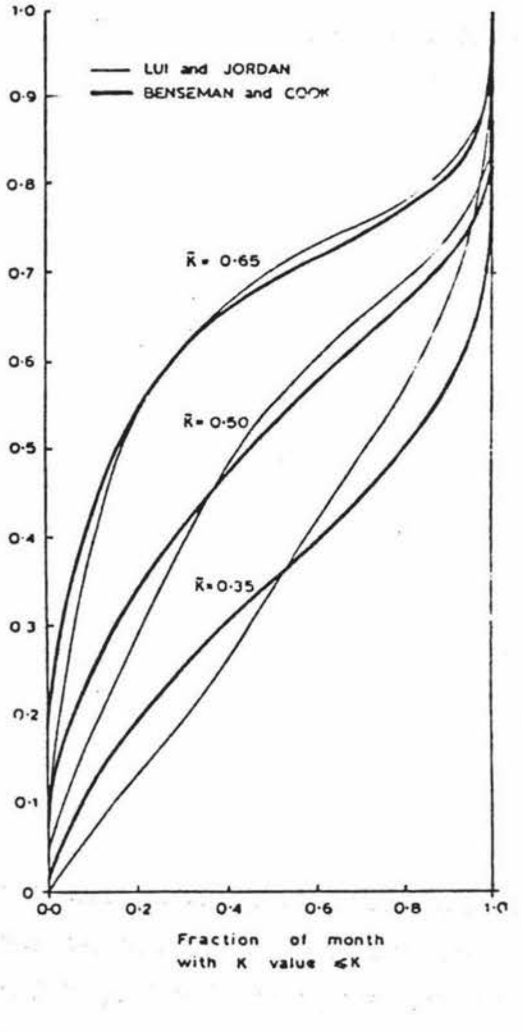


Figure 6.5 The Relationship Between the Average Clearness Index, K, and the Distribution of K throughout the Year (Benseman & Cook, 1969)

It has been found that for all locations and times of the year there is a characteristic distribution of K throughout the month which is a function of the average K for that particular month (Benseman & Cook, 1969). This distribution is shown in figure 6.5. From this distribution the standard deviation values, S, were derived for the New Zealand situation for K values of 0.35. It can be shown that R, where R = S/I, is directly related to the clearness index K. A graph depicting this relationship is shown in figure 6.6.

The battery size for a given month is given by:

$$Q = (CF)\left[(Ca/M) + Cb + (NSR)\right](DL) \qquad (6.24)$$

where:

NSR = the no sun ratio (the ratio of the night load to the total daily load)

DL = the daily demand (kWh/day)

C = days of load

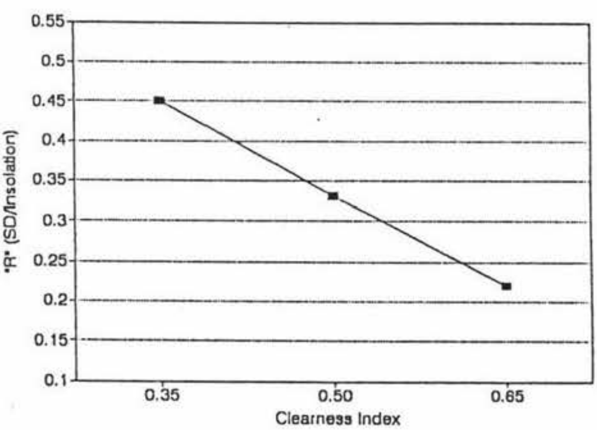


Figure 6.6 R versus the Clearness Index, K

Using the above information and equations, tables were developed by the author for determining the optimum combination of array and battery for different conditions. These are presented in Appendix F for various combinations of array cost/battery cost, battery depth of discharge (DOD), R, average radiation and average demand. Using the computer model a multitude of combinations of array and battery size can be derived which would satisfy the load characteristics. Cost data therefore must be obtained and used within the design tables if the optimum size combination is to be achieved.

It is more accurate to use annualised costs which take into account the lifetime of the components (chapter 10 describes how to do this). The array cost needs to be specified in terms of $ per Wp while the battery storage capacity in terms of $ per kWh of storage. The assumptions in generating the tables were of a battery efficiency of 80%, an array efficiency of 10%, and with 75% of the load demanded during dark periods. It was also assumed, for the analysis, that the standard deviation of radiation on a horizontal surface was approximately equal to the standard deviation of radiation on a tilted surface.

The answers produced by the computer model are for a 1% LOLP.

6.16 Procedure for using the Photovoltaic Design Tables

The steps involved in sizing an optimum array and battery combination are laid out below.

Step 1: The monthly average sunshine hour information for the site are obtained.

Step 2: The global radiation, H, is determined using the tables in Appendix B.

Step 3: After the tilt angle for the different times of the year is chosen, Ht, the radiation received by a plane at that angle, is determined by consulting Appendix E. It is recommended that this radiation level be reduced by about 10% as a safety margin.

Step 4: The annualised cost of the array and battery capacity is determined using table 10.2.

Step 5: The depth of discharge (DOD) figure is selected. R is then calculated where R = S/I. Figure 6.6 may be used to determine R.

Step 6: Using the tables provided in Appendix F, the optimum combination of array and battery pertaining to the specified conditions can be determined.

6.16.1 Example Using Photovoltaic Design Tables

Example: Suppose that the following scenario applies:

Location:	35° South
Month:	June
Sunshine hours:	4.0 hours per day average for the month
Tilt Angle:	55°
Aspect:	North
Demand:	2.0 kWh per day
No Sun Ratio:	75%
Battery Cost:	$420 per kWh
Array Cost:	$15 per Wp
System Efficiency:	10%
Life battery:	7 years
Life array:	15 year
Interest Rate:	17%
Inflation Rate:	12%
Battery DOD:	50%
Battery Efficiency:	80%
S.D. of Radiation:	2 kWh

Step 1: 4 hours sunshine per day

Step 2: From table B2 in Appendix B, where the number of sunshine hours is 4, the month is June and latitude is 35° South:

Average daily radiation is 2.1 kWh per m2.

Step 3: Based on table E8 in Appendix E for a tilt angle of 55°, the month of June, and for where H = 2.1:

$H = 2$: $H_T = 2.9$

$H = 2.5$: $H_T = 4.5$

Interpolation between 2.9 and 4.5, results is a value corresponding to where H = 2.1, of 3.2

kWh/m^2 per day. A margin of safety brings it down to 3.0 kWh/m^2.

Step 4: To determine the annualised cost of the battery and the array, table 10.2 can be consulted.

The discount rate = 17% - 12% = 5%

The discount factor which applies for the array in this situation is 10.4, while for the battery it is 5.79.

Array:	\$14 / 10.4 = \$1.44 / Wp
Battery:	\$420 / 5.79 = \$72.54/ kWh
	AC/BC = 1.44 / 72.54 = 0.02.

Step 5: Maximum Depth of Discharge (DOD) = 50%.

$R = S / I$

$= 2.5 / 5.6 \approx 0.45$

Step 6: Appendix F, table F8 can now be consulted for the parameters summarised below:

Demand	=	2 kWh per day
Radiation	=	3.0 kWh/m^2 per day
AC/BC	=	0.02
R	=	0.45
DOD	=	50%

For a daily demand of 1 kWh it can be seen that the array size requirement is 478 Wp and the battery capacity requirement is 4.5 kWh. These figures need to be doubled for a demand of 2 kWh per day to the following.

Array size requirement: 956 Wp

Battery capacity requirement: 9 kWh for a 1% loss of load probability.

The NSR has no affect on the rating of the array required but does influence the battery capacity. In the above example, when the NSR is taken as 0, that is all of the load occurs during the daytime, the required battery capacity reduces to 6.4 kWh. When the NSR is 100% (all of the load occurs during the night), then the required capacity is then 9.6 kWh.

6.17 Photovoltaic Model Validation

6.17.1 Validation of the Calculation of the Extraterrestrial Radiation

The figures of H_o presented in table 6.2 are marginally higher than those presented by Duffie and Beckman (1980). The reason for this is that the author's model used an updated value for G_{sc} of 1371 /m^2. When the same value of G_{sc} was applied that Duffie and Beckman was used, the same answers were generated. Because K is proportional to Ho, it is important to be aware of how the H_o figures were derived, when using K to determine H.

The Rb values calculated using equation 6.12 and the declination values shown in table 6.1, calculated using equation 6.3, are consistent with those given in Duffie and Beckman (1980).

6.17.2 Validation of the Assessment of the Radiation on a Tilted Surface, Ht.

To ensure that no typographical errors were made in the construction of the author's photovoltaic computer model, results were generated using the model for one of the sites described by Gopinathon (1990) where radiation was both measured and calculated. The results were then compared.

Gopinathon measured global radiation over a period of a year at the National University of Lethosa, Maseru, South Africa (latitude = -29.32°; elevation 1571 m). He used two pryranometers with both sloping towards the equator. One was tilted at an angle of latitude minus 10° and the other at an angle equal to the latitude. Radiation measurements obtained hourly on all of the days of each month were then integrated to determine the daily and monthly average.
An error in one of the equations was discovered in the original reference. This did not, however, carry through to the calculations. It was found in the presentation of the Lui and Jordan model. The second term which represents the ground reflected radiation reads as:

$$H\rho(1+\cos\beta)/2 \qquad (6.25)$$

but should rather read as:

$$H\rho(1-\cos\beta)/2 \tag{6.26}$$

so that the terms cancels out once the collector is horizontal to the grounds surface ie. $\beta = 0°$. The results of this validation are shown for two different angles in tables 6.6 and 6.7. Only daily average radiation values are shown in the tables. The accuracy of the author's computer model generated values was assessed by the mean percentage error (MPE).

$$MPE = \frac{\left\{\Sigma\left[\frac{(M_i - C_i)}{M_i} x 100\right]\right\}}{n} \tag{6.27}$$

where:

C_i is the ith calculated value

M_i is the ith measured value

n is the total number of observations

One can see that there is very good agreement between both the Hay and Lui and Jordan model's calculated value and the measured values. There was no significant difference in accuracy between the values derived by Gopinathon and from the author's computer model. All of the difference is attributable to the slightly different values used for Rb, although the values used by this author are more consistent with those presented in the Appendix of Duffie and Beckman (1980). The maximum difference was 0.2% error which occurred for both models for where the slope equalled the latitude. This is insignificant given that the accuracy of the measurements themselves was assessed at ± 3% (Gopinathon, 1990).

The values generated by the Hay and Lui and Jordan model are very close. Any results will only be as good as the information used within it. While there is very little error in the determination of both H_o and Rb there is a potential for error in the actual measurement of the radiation on a horizontal surface, and in Hd, the diffuse component of this.

6.17.3 Validation of the Determination of Radiation on a Horizontal Surface based on Sunshine Hours

A percentage error was calculated for each month and from these values the MPE (mean percentage error) was found. The results showed good agreement between the measured and the calculated figures. The accuracy of the calculated values was, however, significantly improved where the regional coefficients were considered.

It is interesting that of the 17 sites evaluated, before the application of the regional coefficients, only 2 had a MPE greater than 10% (both of these were less than 12%) and 9 sites had a MPE less than 6%. The average of the MPEs for the values not adjusted by the regional coefficients was 5.5%, while the range was 1.1% to 11.3%. Using the regional coefficients the new range became 1.1% to 8.4%.

CHAPTER 7

WIND POWER

7.1 Introduction

Interest in wind turbines to generate electricity and to pump water is experiencing a revival. The technology associated with it has become both cheaper and more reliable so wind is being increasingly considered as an alternative energy source.

This chapter examines firstly the process of selecting and evaluating a potential wind turbine location. It considers the effect of terrain on wind velocity and turbulence. It then goes on to examine ways of obtaining wind velocity data. Section 7.10 introduces the wind computer model designed by the author. What the model does and how it is achieved is outlined. The last section in this chapter examines the determination of turbine rotor size required for water pumping.

7.2 How Wind is Generated

Wind dissipates the accumulated potential energy resulting from the atmospheric temperature differentials which are generated by the sun shining onto different places of the earth (National Research Council, 1977). Dunn described two principle reasons for the movement of the earth's atmosphere: the unequal amounts of solar radiation received at different latitudes; and the rotation of the earth. Superimposed on these two factors are modifications arising from local disturbances such as the presence of continental land masses.

The amount of solar radiation falling on the outer atmosphere varies with latitude. The band lying roughly 35° north and 35° south receives more energy than it radiates away to space whereas the remaining area radiates more energy than it receives. The balance is restored, partly by a flow of heated air from the equator to the poles, and partly by a similar flow of ocean currents. The wind, which includes the latent heat of the evaporated water, accounts for about 87% of the total heat transfer (Dunn, 1986).

7.3 Power in the Wind

The power in the wind is a function of the velocity of the wind and the density of the air. Equation 2.1 below can be used to calculate the amount of power in the wind.

$$Power = \frac{1}{2} \rho V^3 \qquad (6.1)$$

where:

P is measured in watts per square metre

ρ is the density of the air (1.293 kg/m^3 at STP)

v is the velocity of the wind in metres per second

(Dunn, 1986)

If one ignores minor errors introduced by the small changes in air density then this reduces to:

$$P = 0.6 V^3 \qquad (6.2)$$

(Edwards, 1986)

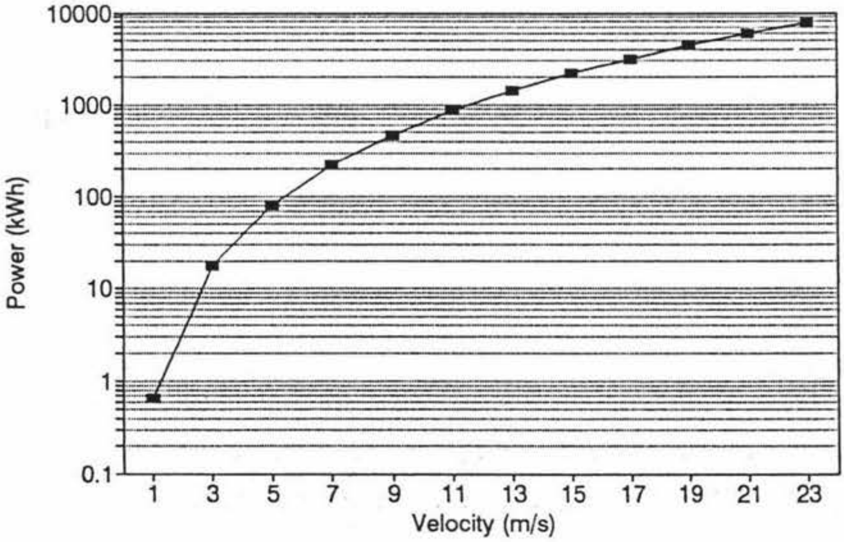


Figure 7.1 Relationship between Velocity and Wind Power

This equation shows that the power is proportional to the cube of the wind speed. For example, a wind with twice the velocity will contain $2^3 = 8$ times the amount of energy. This relationship is illustrated in figure 7.1. It should be noted that the vertical axis has a logarithmic scale.

Because wind power is proportional to V^3, very small changes in wind speed cause large variations in power density. This indicates the importance of a good knowledge of the wind characteristics of a particular site. In New Zealand the annual hourly mean wind power density is about 150 W/m^2 at a height of 10 m, based on a wind speed of 5 m/s (Chilcott, 1975).

7.4 Site Evaluation

Before one rushes into the process of evaluating the wind characteristics for a particular site, a judgement must be made as to which sites are worth further investigation. It is important to ensure that the optimum site is selected.

If a decision is made to evaluate the wind characteristics for a particular site some of the methods used for the initial evaluation may then need to be reexamined in more detail, depending on the availability of accurate meteorological data. Where reliable data is available which is likely to be sufficiently representative of the site in question, this can then be used to go directly on to the next step in the design process.

7.5 General Indicators of Possible Wind Sites

Those who search for wind sites are likely to be in differing circumstances and in differing locations so not all indicators mentioned below will be appropriate for any given situation.

7.5.1 Geomorphological Indicators

Certain features of the land surface, such as sand dunes, are a direct effect of the action of wind. Such features can be detected from satellite or aircraft photographs. They are useful in locating potential areas of strong winds particularly in arid regions (Hiester & Pennell, 1981).

7.5.2 Social and Cultural Indicators

By questioning people who live or work in an area, information about how windy a site is can be obtained, although one needs to bear in mind they generally tend to over-estimate local winds. People working in particular jobs may be particularly well informed. For example, linesmen may have a very good idea of where lines are particularly prone to be blown down.

The Beaufort wind scale (Figure 7.2) can be a useful reference point for relating descriptive terms to actual wind velocity. Conditions above Beaufort number 8 are dangerous for most wind turbine installations (Vosburgh, 1983).

7.5.3 Biological Indicators

The growth habit of certain species of trees, particularly coniferous ones, can be used to obtain an indication of the general 'windiness' of a site. The best known method is called the Griggs-Putman Index as shown in figure 7.3.

7.6 More Specific Indicators of Possible Wind Sites

The following are the main site characteristics which determine its annual average wind speed:

1. topography and exposure,
2. altitude and distance from the sea,
3. geographical position.

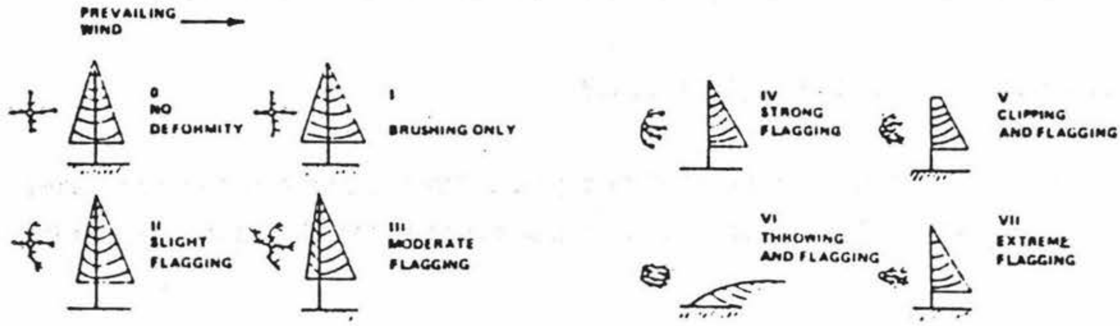
These factors all interact and are of varying significance for different sites. This is readily apparent when one considers that the following features are all often associated with high average wind speeds:

1. gaps, passes and gorges,
2. long valleys extending down from mountain ranges,
3. high elevation plains,
4. exposed ridges, hills and mountain summits,
5. exposed coastal sites.

(Vosburgh, 1983)

Beaufort Number	Descriptive Term	Mean Velocity knots	m/s	km/h	mph	Land	Sea
0	Calm	< 1	0-0.2	< 1	< 1	Calm; smoke rises vertically	Sea like mirror
1	Light air	1-3	0.3-1.5	1-5	1-3	Direction of wind shown by smoke drift but not by wind-vanes.	Ripples with the appearance of scales are formed, but without foam crests.
2	Light breeze	4-6	1.6-1.5	6-11	4-7	Wind felt on face; leaves rustle; ordinary vanes moved by wind.	Small wavelets, still short but more pronounced; crests have a glassy appearance and do not break.
3	Gentle breeze	7-10	3.4-5.4	12-19	8-12	Leaves and small twigs in constant motion; wind extends light flag.	Large wavelets; crests begin to break; foam of glassy appearance; perhaps scattered white horses.
4	Moderate breeze	11-16	5.5-7.9	20-28	13-18	Raises dust and loose paper; small branches are moved.	Small waves, becoming longer; fairly frequent white horses.
5	Fresh breeze	17-21	8.0-10.7	29-38	19-24	Small trees in leaf begin to sway; crested wavelets form on inland waters.	Moderate waves, taking a more pronounced long form; many white horses are formed (chance of some spray).
6	Strong breeze	22-27	10.8-13.8	39-49	25-31	Large branches in motion; whistling heard in telegraph wires; umbrellas used with	Large waves begin to form; the white foam crests are more extensive everywhere (probably some spray).
7	Near gale	28-33	13.9--17.1	50-61	32-38	Whole trees in motion; inconvenience felt when walking against wind.	Sea heaps up and white foam from breaking waves begins to be blown in streaks along the direction of the wind.
8	Gale	34-40	17.2-20.7	62-74	39-46	Breaks twigs off trees; generally impedes progress.	Moderately high waves of greater length; edges of crests begin to break into the spindrift; the foam is blown in well-marked streaks along the direction of the wind.
9	Strong gale	41-47	20.8-24.4	75-88	47-54	Slight structural damage occurs (chimney pots and slates removed).	High waves; dense streaks of foam along the direction of the wind; crests of waves begin to topple, tumble and roll over; spray may affect visibility.
10	Storm	48-55	24.5-28.4	89-102	55-63	Seldom experienced inland; trees uprooted; considerable structural damage occurs.	Very high waves with long overhanging crests; the resulting foam, in great patches, is blown in dense white streaks along the direction of the wind; on the whole, the surface of sea takes a white appearance; the tumbling of the sea becomes heavy and shock-like; visibility affected.
11	Violent storm	55-63	28.5-32.6	103-117	64-72	Very rarely experienced; accompanied by widespread damage.	Exceptionally high waves (small and medium-sized ships might be for a time lost to view behind the wave; the sea is completely covered with long white patches of foam lying along the direction of the wind; everywhere the edges of the wave crests are blown into froth; visibility affected.
12	Hurricane	64 and over	32.7 and over	118 and over	73 and over		The air is filled with foam and spray; sea completely white with driving spray; visibility very seriously affected.

Figure 7.2 Beaufort Wind Scale: Velocity equivalent at a standard height of 10 metres above open flat ground (Edwards, 1986)



- Class O, No Effect. The wind has had no noticeable influence on the tree.
- Class I, Brushing. Small branches and needles appear bent away from the prevailing wind direction. The tree crown may appear slightly asymmetrical. Probably 6-10 mph wind averages.
- Class II, Light Flagging. Small branches and the ends of the larger branches are bent by the wind, giving the tree a noticeably asymmetric crown. Mean windspeeds in the 8-12 mph range.
- Class III, Moderate Flagging. Large branches are bent toward the leeward side of the tree, giving the tree a nearly one-sided crown. Almost good enough for WECS, 11-15 mph average winds.
- Class IV, Strong Flagging. All the branches are swept to the leeward and the trunk is bare on the windward side. The tree resembles a banner. Encouraging for WECS, probably 12-19 mph winds.
- Class V, Partial Throwing, Clipping, and Flagging. A partially thrown tree is one in which the trunk, as well as the branches, are bent to the lee. The trunk may be bent in a concave or convex fashion, but rises vertically near the ground and the degree of bending increases near the top of the trunk. Should be a winning area for WECS. 13-22 mph mean annual winds probable.
- Class VI, Complete Throwing and Flagging. The tree grows nearly parallel to the ground and along the path of the prevailing wind. The larger branches on the leeward side may extend beyond the tip of the trunk. More indicative of storms and danger than encouraging.
- Class VII, Carpeting or Extreme Flagging. The wind is so strong or accompanying conditions so severe (e.g., ice is present) that the tree takes the form of a shrub. Upright leaders are killed and lateral growth predominates. The crown grows across the ground like a prostrate shrub. Dangerous site for WECS. Special design probably required.

Figure 7.3 Griggs-Putman Index (Vosburgh, 1983)

An experienced eye is able to estimate average wind speeds within 20% simply by close observation of the trees! (Vosburgh, 1983).

7.6.1 Type of Terrain

When examining a site an initial assessment must be made of the general terrain. This can be classified as being either flat or complex. For terrain to be classified as flat it must meet the following criteria:

1. site elevation is less than 70 m above or below the surrounding terrain for 5 km in any direction,
2. the maximum slope (h/l) of topographic features within 4 km is less than 3%.

(Frost & Nowak, 1977: cited by Wegley et al, 1980)

In flat terrain it is the surface roughness and the exposure factor which are the two main factors to consider (Edwards, 1986), therefore the procedure is considerably simpler than in complex terrain.

Where complex terrain lies only in a direction from which the wind blows infrequently, it would be generally safe to assume flat terrain (Wegley et al, 1980). If the terrain has been classified as complex then topographic influences are the most significant and ought to be considered ahead of surface roughness and exposure. Turbulence is often a major problem with complex sites and so before the final site is chosen it should be assessed.

Complex terrain potentially offers the following advantages for the use of wind turbines:

1. high relief features reach into faster airstreams,
2. airflow tends to be accelerated, particularly with ridges where the wind is less able to flow around.

(Wegley et al, 1980)

Topographic features can cause significant local variation in near ground surface wind speeds. With low hills (<100m) increases in the wind speed at 30 m above ground level can easily be about 30% compared to a flat terrain site. For some hills a 100% increase in near surface wind speeds occurs, but unfortunately there is currently no formula relating wind speed over a flat piece of ground to that over a hill of a given altitude and shape (Golding, 1976).

7.6.2 Ridges

According to Wegley et al (1980), for potential sites on ridges (defined as elongated hills less than 650 m above the surrounding terrain) the following are the most important considerations:

1. the best ridges or sections of ridges are perpendicular to the prevailing wind,

2. the part of the ridge which has the most ideal slope within several hundred metres of the crest should be selected (refer to table 7.1 and 7.2),
3. excessive turbulence and wind shear should be avoided,
4. if it is not possible to site on the crest of the ridge the next most preferable site is on the end or on the windward slope of the ridge.

7.6.3 Hills and Mountains

For isolated hills and mountains air tends to flow around them more than with ridges. Table 7.1 below is a modified version of a table produced by Wegley et al (1980), which can be used to assess a hill's suitability.

Table 7.1 Wind Turbine Site Suitability Based on Slope

Site Suitability	Slope of the hill near the summit (%)
Ideal	29
Very Good	17
Good	10
Fair	5
Avoid	< 5 and 50 <

(Wegley et al, 1980)

As a general guideline the best location is normally the highest point on a relatively smooth hill or mountain (Fraenkel, 1990).

7.6.4 Cliffs

Siting turbines on cliffs poses special problems as severe turbulence may often be encountered. As with ridges, the prevailing wind ideally flows perpendicular to the cliff or to the section of the cliff where the wind turbine is to be located. For cliffs under 30 m, the best location is between 0.25 and 2.5 the cliff height, down wind from the cliff edge (Wegley et al, 1980). Cliffs greater than this height often create very large turbulent areas.

Table 7.2 Wind Turbine Site Suitability for Isolated Hills

Suitability	Location	Flow Characteristics
Good	Upper half of hills where prevailing wind is tangent	The point of maximum acceleration around the hill
Good	Top of hills	The point of maximum acceleration over the hill
Fair	Upper half of windward face of hills	A slight acceleration of flow up the hill
Avoid	Entire leeward half of hills.	Reduced wind speeds and high turbulence.
Avoid	The foot and lower portions of hills	Reduced wind speeds

(Wegley et al, 1980)

7.6.5 Exposure and Turbulence

Surrounding obstruction, topography and buildings are often responsible for turbulence. Excessive turbulence not only reduces the wind velocity but it also can result in the wind turbine being under considerable stress. The problem can be reduced by locating the turbine on a high enough tower, or well away from the causes of the turbulence.

According to Edwards (1986), useful rules of thumb to avoid turbulence are to site the turbine:

1. upwind a distance of a least 2 times the barrier height,
2. down wind a distance of at least 10 times the barrier height,
3. down wind a height above ground of at least twice the barrier height.

Figure 7.4 depicts a simple way of visually assessing the height at which turbulence remains significant although the same can be done with streamers attached to a balloon or pole at approximately 2 m intervals (Marier,1981).

Towers are used not only to reach faster wind streams but also to get the turbine out of the reach of turbulence. Another commonly accepted rule is to install the wind turbine high enough so that the centre of the rotor is at least 10 m higher than any obstacles within 100 m of the tower (Marier,1981).

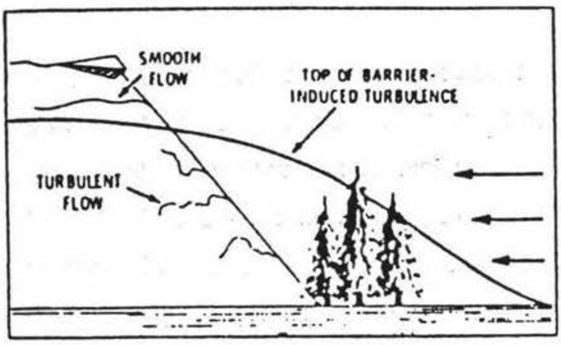


Figure 7.4 Assessing Turbulence (Gipe, 1983)

7.7 Determination of Wind Velocity

One of the most common causes of poor performance of wind systems is the over estimation of the wind energy resource because of inadequate data (Edwards, 1986). Therefore before one is able to determine just how much energy one will be able to harvest from the wind for a given site, the characteristics of the wind regime for the site must be assessed.

One of the first steps in design is to obtain information about the average wind velocity and the duration for which the wind velocity is above a certain minimum. Wind velocity is a prime consideration in design. It must be interpreted to form the basis of estimation of the annual energy which might be extracted by a wind driven generator of a given type and size.

7.7.1 Obtaining Wind Velocity Data

Many libraries hold New Zealand meteorological data published by the New Zealand meteorological service. The bibliography can be consulted for one such publication.
In addition to meteorological stations, universities, existing wind turbine owners, and airports are all potential sources of wind information (Vosburgh, 1983). Because wind exhibits considerable spatial variability it is dangerous to extrapolate data unless there are very few topographical changes between the sites in question (Hiester & Pennell, 1981). As a general rule, sites within 30 km of each other in large areas of relatively flat terrain should have similar wind characteristics provided they have similar exposure to the prevailing wind. In very flat areas this may be

extended to 90 km (Wegley et al, 1980). In rugged, hilly or mountainous terrain, data from a nearby weather station is rarely directly relevant.

It should be kept in mind that where data is collected from airports or meteorological stations, the precise location is often chosen for reasons other than obtaining an accurate estimation of wind velocity (Lalas, 1985) It is thought that the presumption that airport data was taken from consistently well exposed sites led to major errors in the regional wind atlases of the United States (Cherry, unpublished paper). Therefore it is a good idea to visit the recording site in question.

7.7.2 Recording Data

Where wind data is to be recorded on the site as is recommended, monthly wind run measured with a wind run anemometer will usually be adequate (Edwards, 1986). Recordings should be made for at least 12 months depending on the degree of accuracy and confidence level required (Ministry of Energy, 1986; Fraenkel, 1986).

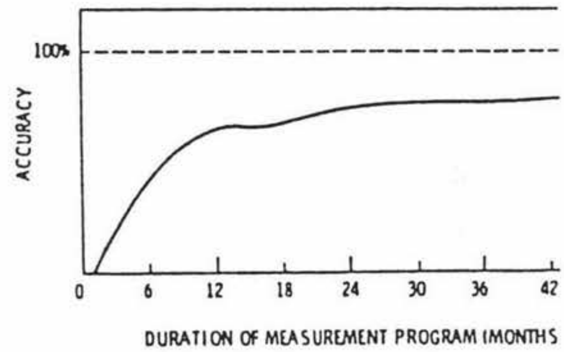


Figure 7.5 Influence of Recording Duration on Accuracy (Wegley et al, 1980)

Figure 7.5 illustrates the effect of increasing the duration of data collection on accuracy.

If the energy demand is seasonal, wind data may be collected over that season (Marier, 1981). Such instruments may be hired from the Meteorological service.

7.7.3 Equipment for Wind Speed Measurement

Anemometer

These are usually made as miniature turbines consisting of either funnel shaped cups or a small rotor which turns a small generator. The electrical signal varies with the speed of the wind. Most anemometers are also equipped with a wind direction indicator (Marier,1981).

Oedometer (also called accumulators)

This is a simple type of recording anemometer. It records the number of revolutions that the anemometer makes as a distance figure which is termed wind run. The average wind speed is then found by dividing the wind run by the time over which the recordings were taken (Marier,1981).

7.7.4 Height Correction and Surface Roughness

Wind flowing over the earth's surface encounters friction and this serves to slow it down. As expected, this slowing effect of the earth's surface decreases in increasing height until the friction effect is negligible. Wind velocities are normally measured at a height of 10 m, so if data taken at one height is to be applied to another, it must be adjusted.

Surface Roughness

Rougher surfaces create more friction as the air moves over them, therefore slowing it down more. They also tend to generate turbulence while a smooth surface, like the sea or a flat grassy plain, allows the air to flow smoothly which results in higher wind speeds nearer to the surface. Surface roughness provides a clue as to how one site might compare to another as well as giving an indication of how wind velocity might change according to height.

It has been found that wind velocity increases with height according to the relationship expressed in equation 7.3:

$$\frac{V_1}{V_2} = \left[\frac{Z_1}{Z_2}\right]^x \qquad (7.3)$$

where:

V_2 is the wind velocity at some reference height Z_2

V_1 is the velocity at height Z_1.

'x' is a constant determined by the nature of the surface.

The value of the constant 'x' is determined by the surface roughness.

When this change in speed with height is represented graphically it is called the speed profile. The shape of the profile is determined principally by roughness, however, temperature also plays an effect, albeit an insignificant one (Gipe, 1983).

Table 7.3 Typical Values of Surface Roughness

Type of Terrain	x value
Smooth sea or sand	0.10
Low grass steppe	0.13
Flat grassy surfaces	0.17
High grass and small bushes	0.19
Woodlands and urban areas	0.32

(Frankel, 1986; Dunn, 1986).

7.7.5 Extrapolation of Data to Other Areas

Adjustment can be made using table 7.4 (which assumes the anemometer height was 10 m and the surrounding roughness is that of high grass). For a proposed site with a certain roughness characteristic, one moves down until the multiplication factor for the proposed height of turbine operation is reached. This is then multiplied by the wind velocity at the anemometer station. This method should not be applied in very hilly country.

Figure 7.6 can also be used to assist in the adjustment of wind data from one site to another. The factor 'F' represents the ratio between the wind velocity and the wind measured in a standard exposure (Class II) and standard height (10 m). A line is drawn for each of the five roughness classes, as described below:

I Sea or Lake shore with no more than 5 km fetch over the water
II Flat terrain with some isolated obstacles
III Rural areas with low buildings and hedges
IV Urban, industrial or forest areas
V Large city centres

Table 7.4 Wind Velocity Extrapolation Factors for Sites in Areas of Different Surface Roughness

Height above ground(m)	Smooth Surface	Low Grass	High Grass	Tall Row Crops	High Woods	Suburbs
6	1.40	1.02	0.92	0.88	0.60	0.37
9	1.45	1.10	1.00	0.97	0.70	0.48
12	1.50	1.16	1.06	1.05	0.77	0.55
18	1.56	1.24	1.14	1.11	0.86	0.66
24	1.60	1.29	1.20	1.17	0.93	0.74
30	1.63	1.34	1.25	1.22	0.99	0.80
36	1.66	1.37	1.28	1.26	1.03	0.84
42	1.68	1.40	1.32	1.29	1.07	0.89
49	1.70	1.43	1.34	1.32	1.10	0.92
55	1.72	1.45	1.37	1.34	1.13	0.95
61	1.74	1.47	1.39	1.36	1.15	0.98

(modified Wegley et al, 1980)

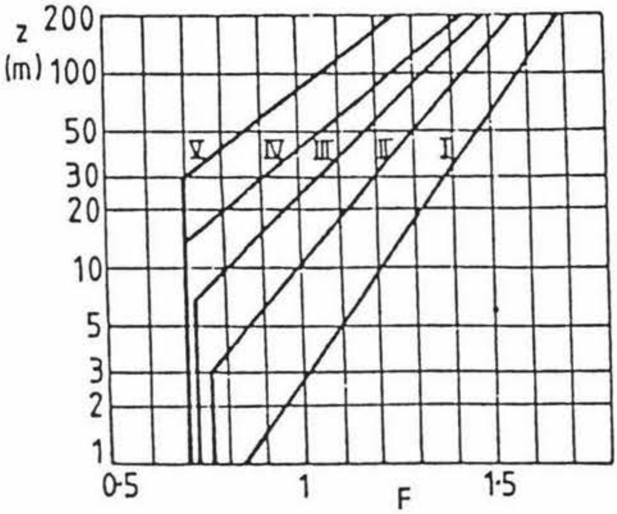


Figure 7.6 Extrapolation of Wind Velocity Information to Areas with Differing Roughness (Edwards, 1986)

7.8 Types of Wind Turbines.

Figure 7.7 illustrates the most common forms of wind turbines.

The choice of turbine will depend on the use for which the power is required. For water pumping using positive displacement reciprocating pumps, a high starting torque and a low starting speed is required, whereas for electricity generation the starting torque requirement is small but a high speed is desirable (Dunn, 1986). Some types of wind turbines lend themselves more to readily to a particular revolution rate and starting torque.

7.8.1 Horizontal Axis Wind Turbines

This is the common and most widely studied of all turbine types (Nahas et al, 1987). The modern ones commonly have either two or three blades. They are normally not suitable for water pumping directly because of the low torque they generate and because of their rapid speed of rotation. This is not true of the horizontal axis wind turbines with many blades as they produce a higher torque and a lower speed.

All of the wind turbine design charts in the Appendix and most of what is written in this thesis refers to this type of wind turbine.

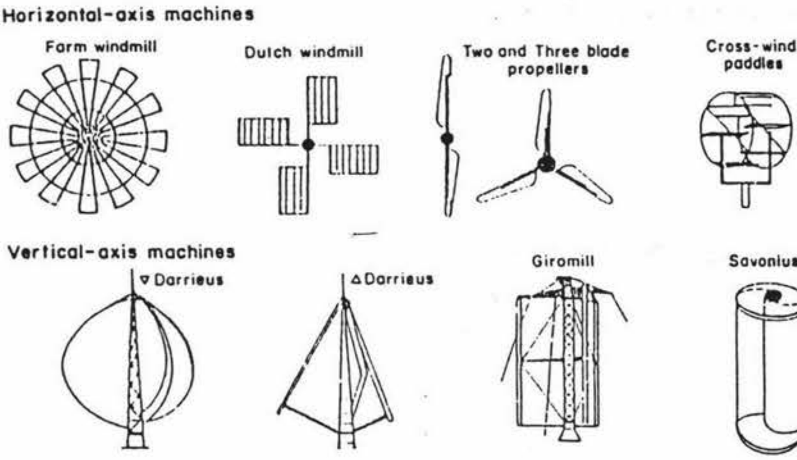


Figure 7.7 Common Types of Wind Turbine

7.8.2 Savonius

The advantages of the Savonius type are described as follows: simple design; low manufacturing cost; ease of construction; self starting; and able to deliver high torque at a low wind speed. Some of its applications include water pumping, ventilation, agitation, and others where the rotor is connected via mechanical means directly to the load.

The Savonius is the simplest and the cheapest of all turbines. It is, however, not suited to electricity generation because of its relatively low rotor speed, efficiency and power output.

The effect of seven design parameters on the aerodynamic performance of savonius rotors was determined by Ushiyama and Nagai (1988). These parameters are illustrated in figure 7.8.

The following conclusions were reached:

1. a large aspect ratio (AR) provides the rotor with good torque and power characteristics (AR = 4.29 was optimum),

2. an overlap of 20% to 30% is desirable for semi-circular buckets,
3. a small negative gap is desirable,
4. the Bach type of cross sectional profile is desirable,
5. the two bucket type is more appropriate than the three bucket,
6. the double stack rotor is slightly superior to the corresponding single stack rotor,
7. bucket endplates greatly enhance performance.

(Ushiyama & Nagai, 1988)

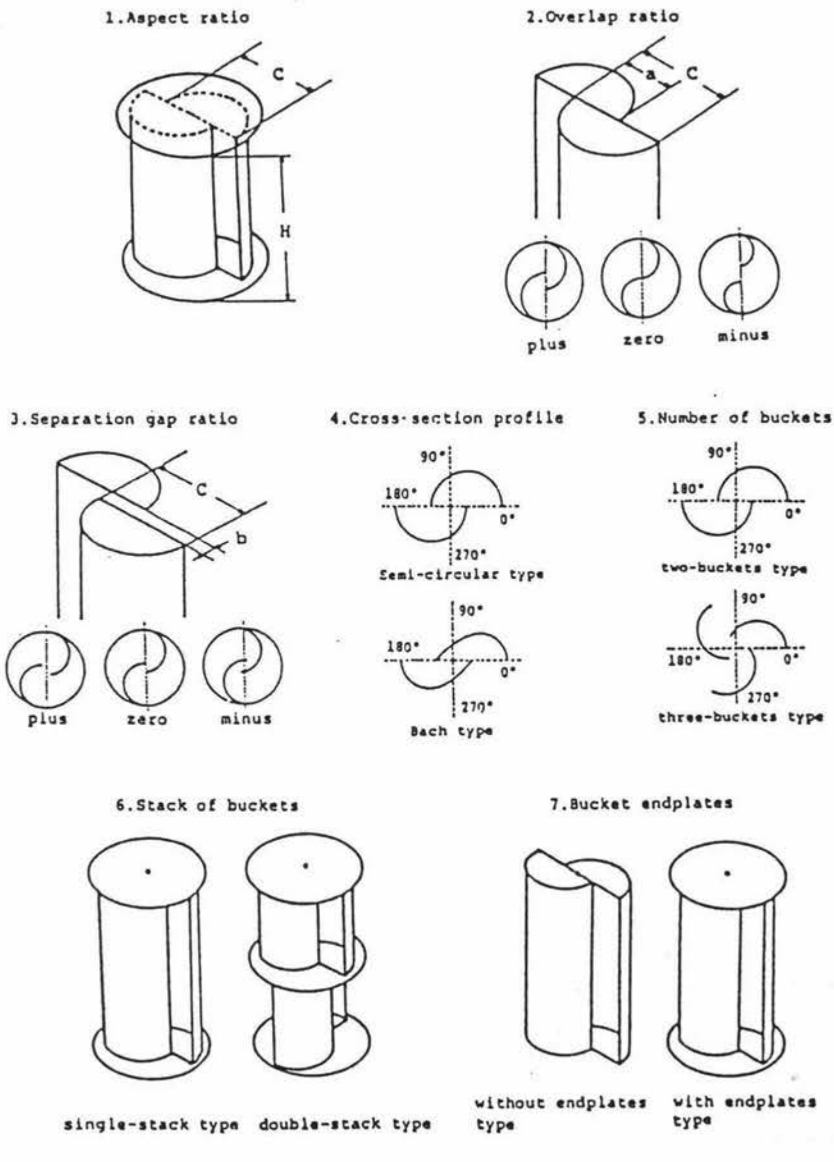


Figure 7.8 Savonius Rotor Design Parameters (Nahas et al, 1987)

7.8.3 Darrieus

The advantages of this type of turbine are: the power take off (PTO) is at or near ground level, the power output per unit mass is the highest of all the types of wind turbines; and it can generate electricity and pump water. Its main disadvantage is that it has a low starting torque and so requires some external means of starting. It also suffers high centrifugal forces resulting in large bending stresses in the blades (Nahas et al, 1987).

7.9 Electricity Generation

A wind turbine producing electricity has a lower overall efficiency than a mechanical system yet it offers greater flexibility in adapting to varying loads. For electricity generation the starting torque requirement is small but a high speed is desirable (Dunn, 1986).

7.9.1 Generator

An ideal generator for use with a wind turbine would have the following features:

1. a low operating speed suitable for direct coupling to the wind turbine,
2. an output of DC or three phase AC,
3. capable of self-excitation,
4. robust construction,
5. no drag torque until threshold speed is reached.

(Menzies et al, 1980)

Unfortunately there are no such generators on the market so some compromises need to be made. A problem often encountered with generators is that of brush wear. Particularly in areas which experience low humidity or freezing temperatures, special brushes need to be used (Menzies et al, 1980). Generators are now available which do not require brushes and are preferable for many situations. Brushless generators, which use an electromagnetic field to transmit excitation current, require less maintenance (Inversin, 1986).

'Mains' compatible electricity is produced with a wind turbine in two main ways. One is to use an induction generator, essentially operating at a fixed rotor speed with a variable tip-speed ratio, while the other is to use an alternator connected to a line commutated inverter (Vosper & Clark, 1988). Use of an induction generator (which runs at a constant rpm) means that the rotor also runs at a constant rpm instead of the constant tip-speed ratio.

There is a maximum size generator for any given rotor size beyond which there is no advantage in terms of energy production (Cromack & Oscar, 1984). Most generators used with wind systems are of the synchronous alternating current type. Alternators, although supplying a constant frequency, demand a constant speed (Golding, 1976). An induction motor is able to be used in reverse mode as an induction generator but can have problems of excitation and of voltage control (Giddens, 1986). An advantage of DC generators with wind systems is that a variable speed of rotation is practical. DC generators and accumulators are therefore commonly used instead of alternators.

Where a wind generator is used in combination with battery storage, a rectifier needs to be used to convert 230 V AC to 110 V DC for battery charging. An inverter and transformer will also be needed to convert the 110 V DC from the batteries back to 230 V AC for appliance use (Charters, 1986). The rotational speed, voltage, and frequency of the output of a wind driven asynchronous generator are all proportional to the wind speed. It is preferable that a variable voltage (V) and frequency (f) system operate at a constant V/f, close to that specified by the name plate on the motor (Vosper & Clark, 1988).

7.10 Introduction to the Wind Turbine Computer Model

A computer model has been created by the author. This has been used to generate design information which has been presented in various tables in the Appendix. Following the description of the model's outputs below, section 7.10.1 describes some of the theory behind the model's operation. The wind pumping theory is dealt with separately in section 7.11.

The outputs of the model are as follows:

Wind Velocity Distribution

This is the time the wind blows at any given velocity. Appendix H shows the wind velocity distribution tables for an average wind velocity of 5 through to 10 m/s and for each velocity a shape factor (section 7.10.1 discusses this) of 1.5, 1.8, and 2.0. These show the probability that the wind velocity will exceed a particular velocity and the expected number of hours the wind will blow at any given velocity. This information is of prime importance in wind turbine design and selection.

The same data is also displayed in the form of wind speed frequency distribution graphs in Appendix I. These graphs are useful because they show the shaped curve corresponding to a given average velocity and shape factor. By plotting known data points from a site similar to the one in question and then comparing the shape of the graph to those provided, the shape factor applicable is able to be determined.

Wind Power Duration

This is the energy delivered by the wind at any velocity for a particular site. This information is also shown in the tables in Appendix H for the same combinations of wind velocity and shape factor. The corresponding wind power duration curves are shown in Appendix J. The graphs are important because they enable a quick visual assessment of the wind profile to be made and so approximate turbine parameters able to be determined while the tables enable the wind profile characteristics to be quantified.

Annual Turbine Power Output

Tables in Appendix G enable the annual output from a turbine, with given characteristics to be determined operating in a specified wind regime, to be approximated. They are all based on a shape factor, k, with a value of 2. The turbine parameter combinations which are covered by the tables are as shown in table 7.5.

Table 7.5 Turbine Parameters for which Power Output Tables have been Produced

Cut-in Velocity	Rated Velocity	Furling Velocity
3	7	15
3	7	20
3	9	15
3	9	20
3	11	15
3	11	20
4	8	15
4	8	20
4	10	15
4	10	20
4	12	20
4	12	25
5	9	15
5	9	20
5	11	20
5	11	25
5	13	20
5	13	25

Power output values are provided for the above turbine parameters when combined with an average wind velocity of 3 through to 10 m/s, and with a rated output of 0.5 through to 10 kW.

The following is an example using the power duration curves:

For example, if 25% of the wind's energy at a particular site lies in velocities between 3 and 5 m/s, a cut-in velocity of over 3 m/s would be appropriate. Similarly, if 90% of the wind's energy lies below 15 m/s, there is then little advantage in selecting a turbine with a furling velocity of 25 m/s.

Sizing a Wind Pump Rotor

Where wind power is to be used for pumping water, nomograms have been provided (figures 7.15, 7.16 and 7.17) to enable the determination of the rotor size required under given wind conditions. These cover average wind speeds of 4 to 10 m/s, shape factors of 1.5, 1.8 and 2.0, and a volume-head product of 1,000 to 10,000 m^4 per day.

Examples of the use of these various design tables are included in the text. Section 7.11 deals with wind pumping in some detail.

7.10.1 Basic Theory Behind Models Operation

Wind Frequency Distribution

The frequency of occurrence of wind velocities and the wind velocity distribution, can be related to the average wind velocity. This has been done by the use of the two parameter Weibull distribution which can be expressed as follows:

The fraction of time that the wind velocity exceeds V (the average velocity) is given by equation 7.4:

$$Probability\ (velocity \geq V) = \exp(\ [V/C]\ k) \tag{7.4}$$

(Edwards, 1986)

'C' is the Weibull Scale Factor and is related to the average wind velocity by the relationship expressed in equation 7.5:

$$C = 1.125\ V \tag{7.5}$$

The Raleigh Distribution is modelled when the shape factor, k, has a value of 2 in the Weibull Distribution and this value has been used in the determination of the turbine power output tables in Appendix G. Turbulent winds may have a value of 1.8 or less, while the value for Caribbean trade winds may be 2.5 or greater. The New Zealand wind energy resource survey by Cherry (1987), showed that the deviations from the Raleigh distribution for New Zealand were not of practical significance in a conservative design. It has been found that the wind velocity distribution patterns are sufficiently constant from year to year for a close estimation of the energy to be made in this manner (Golding, 1976).

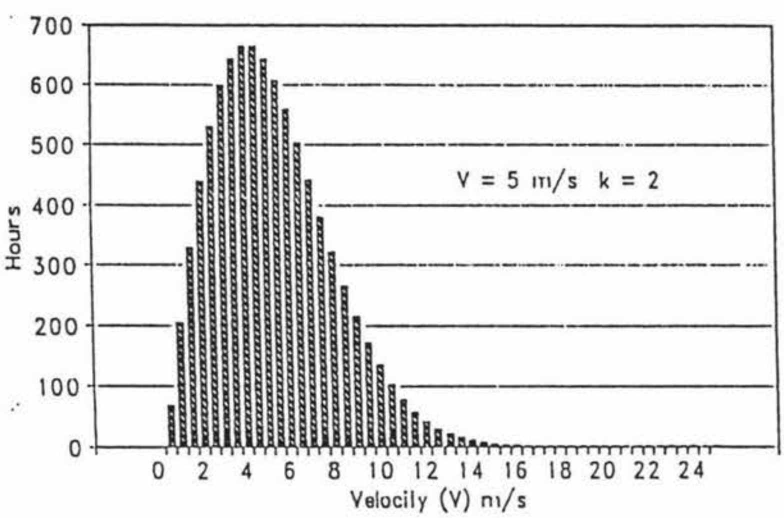


Figure 7.9 Wind Speed Frequency Distribution

Wind Power Duration

The energy delivered by the wind at any given velocity is determined by the product of the number of hours at a velocity, and the power in the wind at that given velocity. The former figure is given by the wind speed frequency distribution.

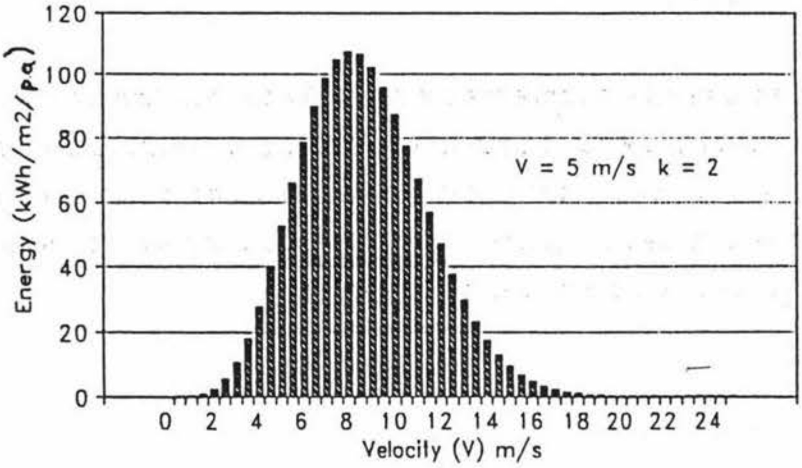


Figure 7.10 Wind Power Duration Curve

Turbine Power Output

The turbine power output is based on the turbine parameters of cut-in wind velocity, rated wind velocity and furling wind velocity. To determine this, the three parameters are examined separately. For the purposes of calculating wind turbine output, the power output curve has been assumed to have a shape represented by figure 7.11.

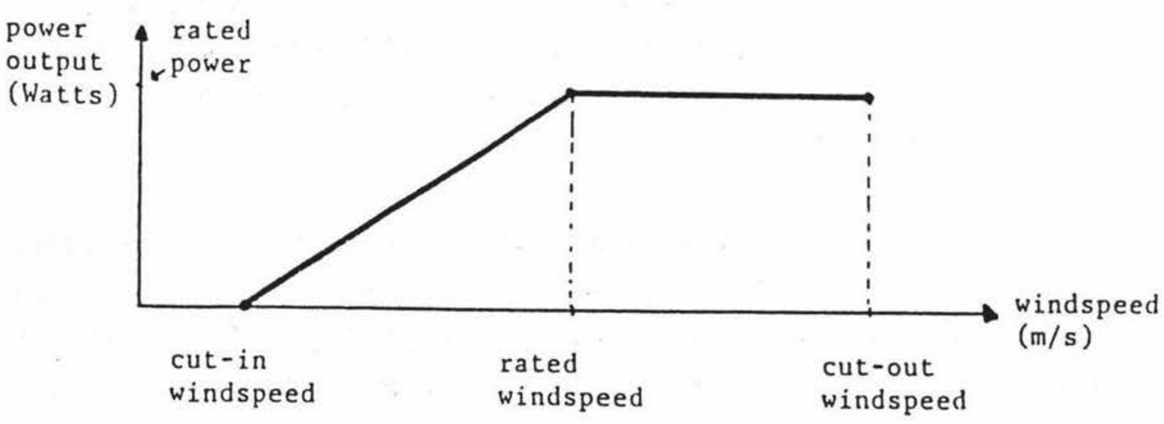


Figure 7.11 Standard Turbine Output Curve

The turbine begins to produce power at its cut-in velocity. As the wind velocity increases, so too, does the output of the generator. The turbines reaches full output (rated output) at a wind velocity called the rated wind velocity.

The computer model checks if the velocity is above the cut-in velocity but less than the rated velocity. If it is, the turbine is producing power but less than its rated output. A linear relationship has been assumed between the power output at the cut-in velocity and the rated output at the rated velocity. This closely represents the real situation for most turbines. Summing the turbine output for each of the wind velocities gives the total annual power output.

Simple Example to Illustrate the Use of the Design Tables

Assuming the following scenario:

Wind Regime

Average Annual Velocity:	5 m/s
Annual Demand:	3,500 kWh

Step 1: The power demand must be first determined. Chapter 5 deals with the assessment of electrical and water demand in some detail.

Step 2: Turbine characteristics must be estimated. It is assumed that there is an average wind velocity of 5 m/s and a shape factor of 2. The corresponding wind power duration graph with an average velocity of 5 m/s and a shape factor of 2 can then be consulted, or alternatively, the Weibull distribution table H1 in Appendix H used.

From figure 7.10 one is able to see that most of the energy is produced by the wind velocities between 5 and 14 m/s. This is able to be quantified by using Appendix H. Consulting the third column in the Weibull distribution table H1, the amount of energy falling outside those velocities can be calculated. 156.2 kWh/m^2 is the amount of energy produced by winds less than or equal to 5 m/s, and 59.6 kWh/m^2 is produced by winds greater than or equal to 14 m/s. The sum of these figures is 215.8 kWh/m^2.

The total amount of power in the wind is 1490 kWh/m^2 so 215.8 kWh/m^2 represents only 15% of the available power. On the basis of this and other similar calculations, a wind turbine's optimum characteristics can be estimated.

Step 3: The turbine output can now be determined

By consulting the various tables in Appendix G, the output of a turbine whose characteristics are mentioned above, may be determined. The annual power output from such a turbine rated, at 6 kW from the table for the above turbine characteristics and wind velocity, is 2250 kWh. To make a more conservative estimate and to allow for maintenance and breakdowns, the figure derived from the table should be reduced by 10%.

$$0.9 \times 2250 = 2025 \text{ kWh.}$$

The final selection of turbine will be also influenced by economics and availability.

7.10.2 Validation of Computer Model Turbine Output

Cherry (1987) modelled the output of a turbine suitable for use in wind farms. The turbine characteristics were:

Cut-in Wind Velocity:	6 m/s
Rated Wind Velocity:	14.8 m/s
Furling Wind Velocity:	20 m/s
Rated Output:	2500 kW
Average Wind Velocity:	7 m/s

The turbine power output figures shown in Table 7.6 were derived from the computer model using the above turbine characteristics. The figure corresponding to a turbine rated power of 10 kW at an average wind velocity of 7 m/s, is 21520 kWh. Turbine output is directly proportional to rated power so for a turbine with a rated power of 2500 kW, the output equals 21520 x 250 = 5.38×10^6 kWh. This equates to 19.4×10^6 MJ (3.6 MJ = 1 kWh). The model Cherry (1987) used included a reduction of 10% to allow for maintenance and breakdowns.

$$19.4 \times 10^6 \times 90\% = 17.5 \times 10^6 \text{ MJ}$$
$$= 17.5 \text{ TJ}$$

In comparison, Cherry's method produced a figure of 18.7 TJ (ie 6% more than the computer generated result).

Table 7.6 Power Produced by Turbine per Annum: Validation Example

Turbine Characteristics

Cut-in Velocity =	6	m/s
Rated Velocity =	14.8	m/s
Furling Velocity =	20	m/s

Turbine Rated Pwr (kW)	Average Wind Velocity (m/s) 3	4	5	6	7	8	9	10
0.5	30	160	410	730	1080	1410	1680	1880
1.0	60	330	820	1460	2150	2810	3360	3770
1.5	90	490	1230	2190	3230	4220	5040	5650
2.0	120	660	1640	2920	4300	5630	6720	7530
2.5	150	820	2050	3650	5380	7040	8410	9420
3.0	180	980	2460	4380	6460	8440	10090	11300
3.5	210	1150	2870	5110	7530	9850	11770	13180
4.0	240	1310	3280	5840	8610	11260	13450	15070
4.5	270	1470	3690	6570	9680	12670	15130	16950
5.0	304	1638	4104	7303	10761	14074	16810	18833
5.5	330	1800	4510	8030	11840	15480	18490	20720
6.0	360	1970	4930	8760	12910	16890	20170	22600
6.5	390	2130	5340	9490	13990	18300	21850	24480
7.0	430	2290	5750	10220	15070	19700	23530	26370
7.5	460	2460	6160	10950	16140	21110	25220	28250
8.0	490	2620	6570	11680	17220	22520	26900	30130
8.5	520	2780	6980	12410	18290	23930	28580	32020
9.0	550	2950	7390	13140	19370	25330	30260	33900
9.5	580	3110	7800	13880	20450	26740	31940	35780
10.0	610	3280	8210	14610	21520	28150	33620	37670

Marier (1981) estimated various turbines outputs for different average wind velocities with a shape factor of 2. These were presented along with manufacturer's estimates. Results generated using the procedure described in this study are compared to these two estimates below:

Dakota 'BC4'

Rated Output:	4 kW
Cut-in Velocity:	8 mph (3.56 m/s)
Rated Velocity:	27 mph (12 m/s)
Furling Velocity:	40 mph (17.78 m/s)

Estimated Output @ average wind velocity 14 mph (6.22 m/s)

Manufacturer:	1000 kWh per month
Marier:	826 kWh per month
Author:	1100 kWh per month

Aeropower 'SL 1500'

Rated Output:	1.4 kW
Cut-in Velocity:	6 (2.66 m/s)
Rated Velocity:	25 mph (11.11 m/s)
Furling Velocity:	100 mph (44.44 m/s)

Estimated Output @ average wind velocity 12 mph (5.33 m/s)

Manufacturer:	258 kWh per month
Marier:	366 kWh per month
Author:	384 kWh per month

Sencenbaugh '1000'

Rated Output:	1.0 kW
Cut-in Velocity:	6 mph (2.67 m/s)
Rated Velocity:	23 mph (10.22 m/s)
Furling Velocity:	60 mph (26.67 m/s)

Estimated Output @ average wind velocity 12 mph (5.33 m/s)

Manufacturer:	380 kWh per month
Marier:	351 kWh per month
Author:	396 kWh per month

As seen by the above three results there is a significant degree of variation between the results. While it is not stated, Marier may have generated his estimates using actual turbine output data for each wind speed while this author used only cut-in, furling and rated values. The degree to which the actual turbine output represents this straight line assumption, depicted in figure 7.11, plays a significant role in just how accurate the estimates will be. Also, the longer the turbine operates at the rated output the more accurate the estimates will be. Wherever possible it is preferable to use manufacturer's data.

It was not stated if any allowance had been made in the estimate by Marier and the manufacturers for breakdowns and maintenance. If allowance had been made it might partially explain why the results of this author are consistently higher, in the case of the first turbine, exactly 10% higher than the manufacturers estimate.

7.11 Determining the Turbine Size Required for Water Pumping

Particularly in developing countries wind is often used to pump water, so guides are included in this study to enable the wind rotor size to be approximated for given conditions of flow, head, average wind velocity, wind shape factors, head and flow.

7.11.1 Determining Pumping Head

Assuming the water requirement is already known, the next step is to determine the pumping head. This is the vertical distance that the pump must raise the water. It can be calculated by summing the following components which are illustrated graphically by figure 7.12. According to Lancashire et al (1987) the components are as follows:

1. the distance from the ground to the water level when the pump is not running,
2. the draw down. That is the difference between 1. and the water level when the pump is running. This is generally determined from test results,
3. the difference between the top of the water level in the storage tank and the ground level at the bore,
4. all of the friction losses associated with the pipe (table 7.7 can be referred to for assistance in the determination of this).

7.11.2 Volume-Head Product

A convenient expression to use is the volume-head product which is measured in m^4/day for each month. The volume-head product is simply the volume of water required, multiplied by the total head. The month with the highest volume-head product should be used for this calculation.

7.11.3 Sizing the Rotor using the Design Nomograms

Figure 7.13, 7.14 and 7.15 are sizing nomograms created by the author with which the rotor required for a given volume-head product, operating in a given wind regime, may be determined. Although the nomograms are based on an overall efficiency of 10%, table 7.8 can be used to adjust for different efficiencies. To use the table, the rotor diameter determined from the nomogram needs to be multiplied by the correction factor to obtain the true rotor diameter required.

Section 7.11.6 provides an example of the use of these nomograms and correction factors.

Table 7.8 Adjusting for Different Overall Efficiencies in Wind Pump Nomograms

Overall Efficiency	Correction Factor
15	0.82
14	0.85
13	0.88
12	0.91
11	0.95
10	1.00
9	1.05
8	1.12
7	1.20
6	1.29
5	1.41

TOTAL PUMPING HEAD = WATER REST LEVEL + DRAW DOWN + HEIGHT OF TANK + PIPEWORK HEADLOSS

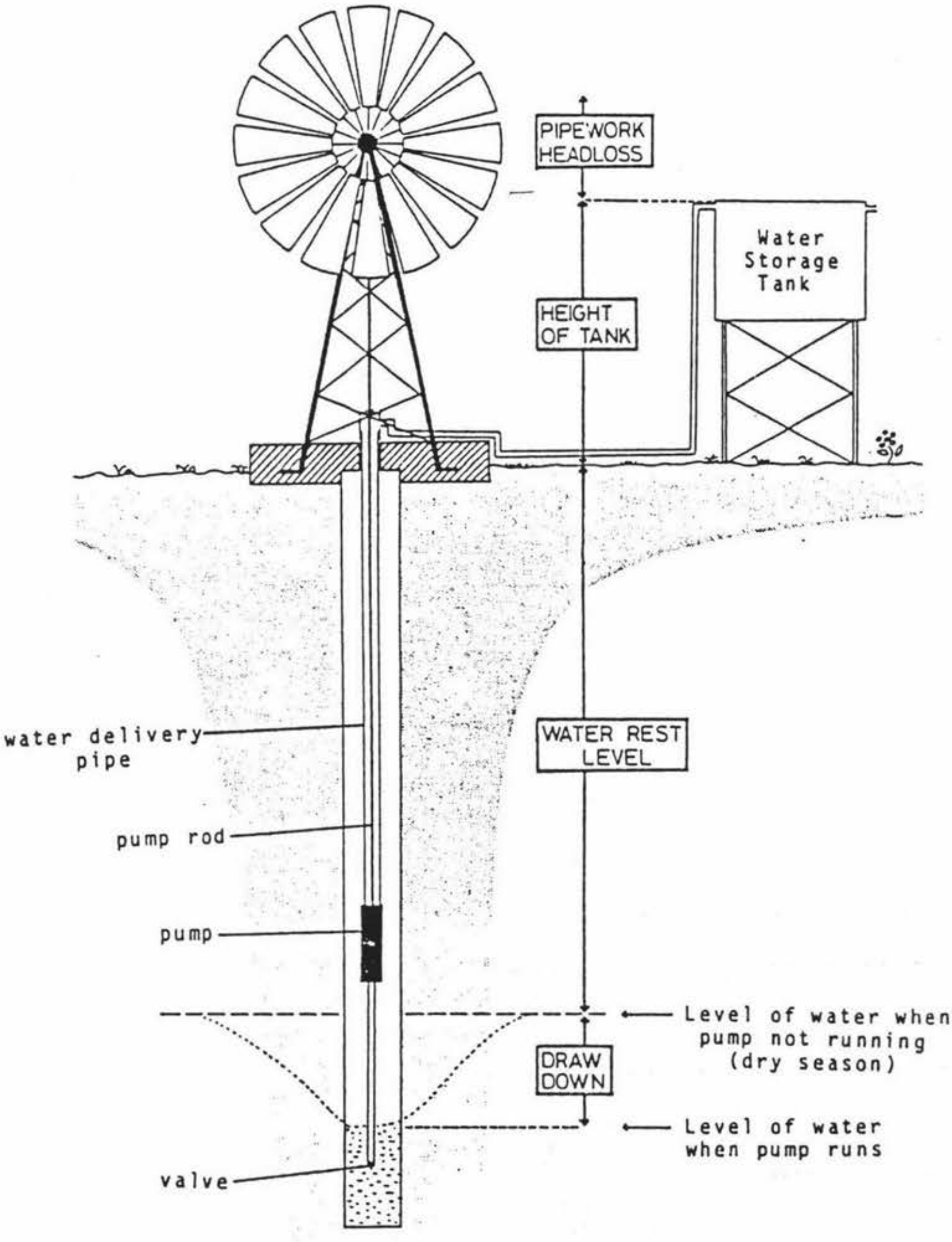


Figure 7.12 Schematic Representation of Wind Pumping Head Components (Lancashire et al, 1987)

Table 7.7 Headloss in metres per 100 m of Pipe Length for Various Flow Rates and Pipe Diameters

	PIPE DIAMETER				
mm	25	37	50	75	100
in	1	1	2	3	4
FLOW-RATE m3/d					
10	0.50	0.10	0.02	0.00	0.00
20		0.43	0.07	0.01	0.00
30		0.90	0.20	0.02	0.01
40		1.60	0.30	0.04	0.01
50			0.50	0.06	0.02
60			0.70	0.09	0.02
70			1.00	0.12	0.03
80			1.30	0.16	0.04
90			1.60	0.20	0.05
100			2.00	0.25	0.05
110				0.30	0.06
120				0.35	0.08
150				0.60	0.12
200				1.00	0.20
300					0.45

(Lancashire et al, 1987)

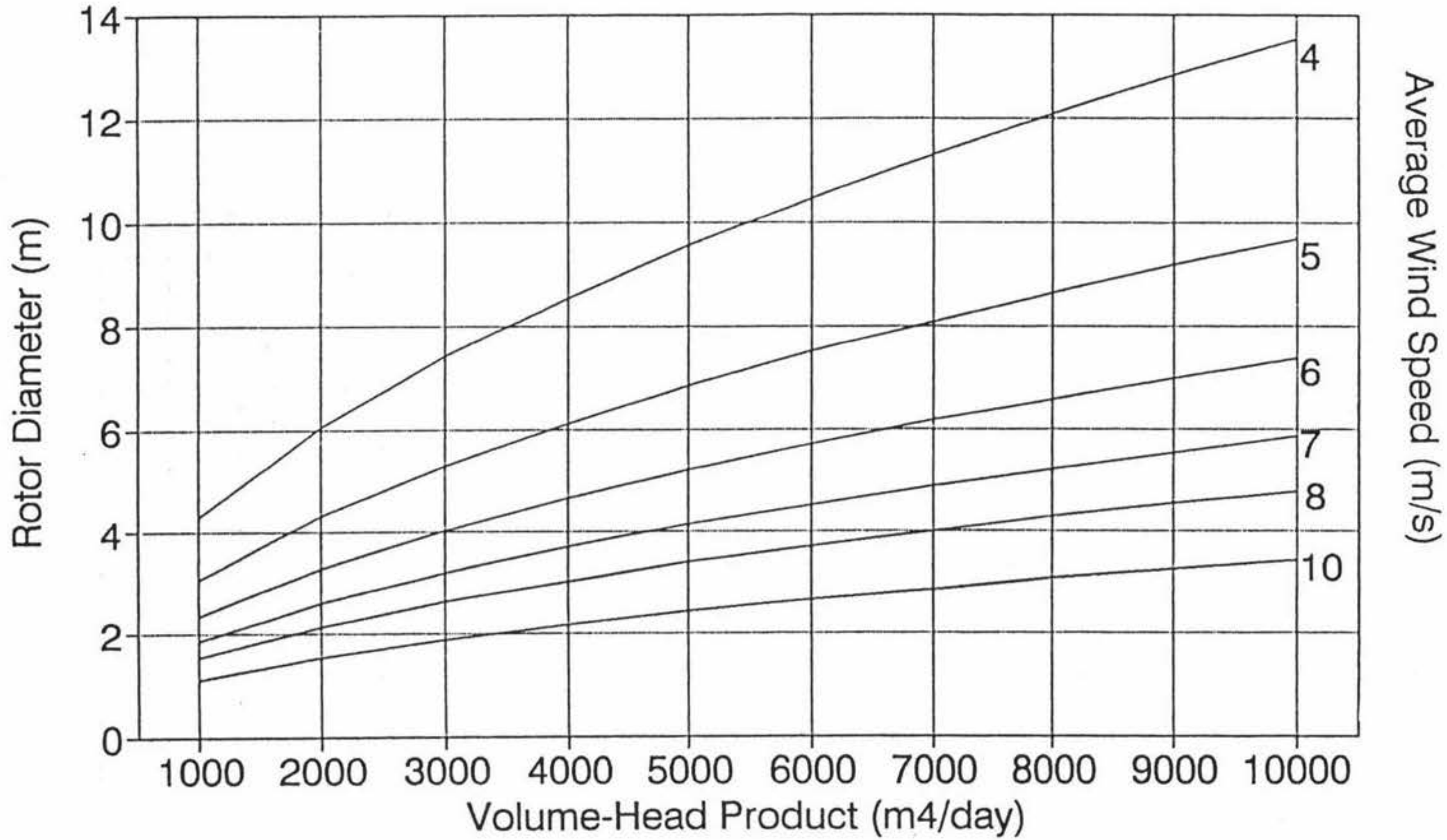


Figure 7.13 Nomogram for Sizing Wind Pump Rotor (EPF 1.9)

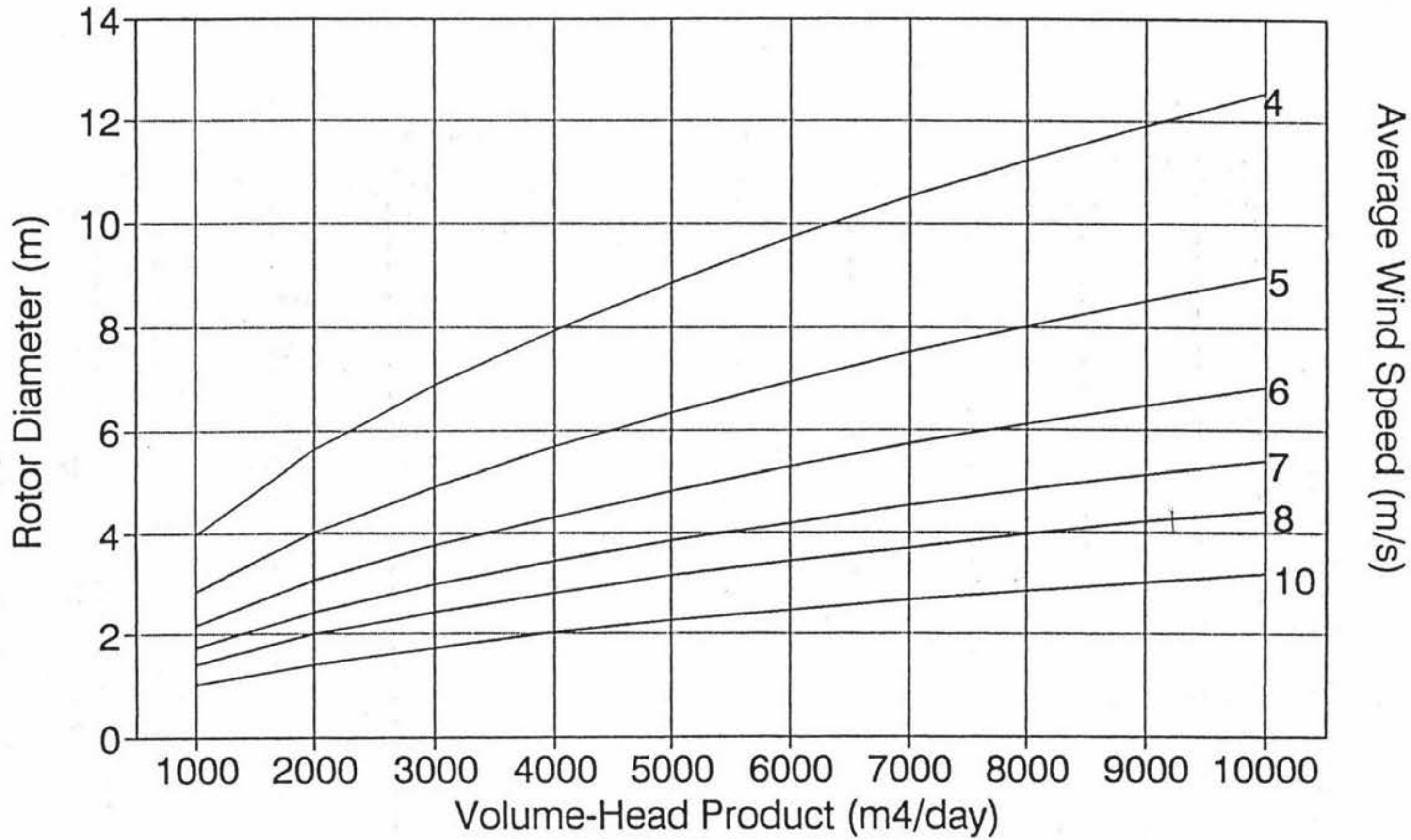


Figure 7.14 Nomogram for Sizing Wind Pump Rotor (EPF 2.2)

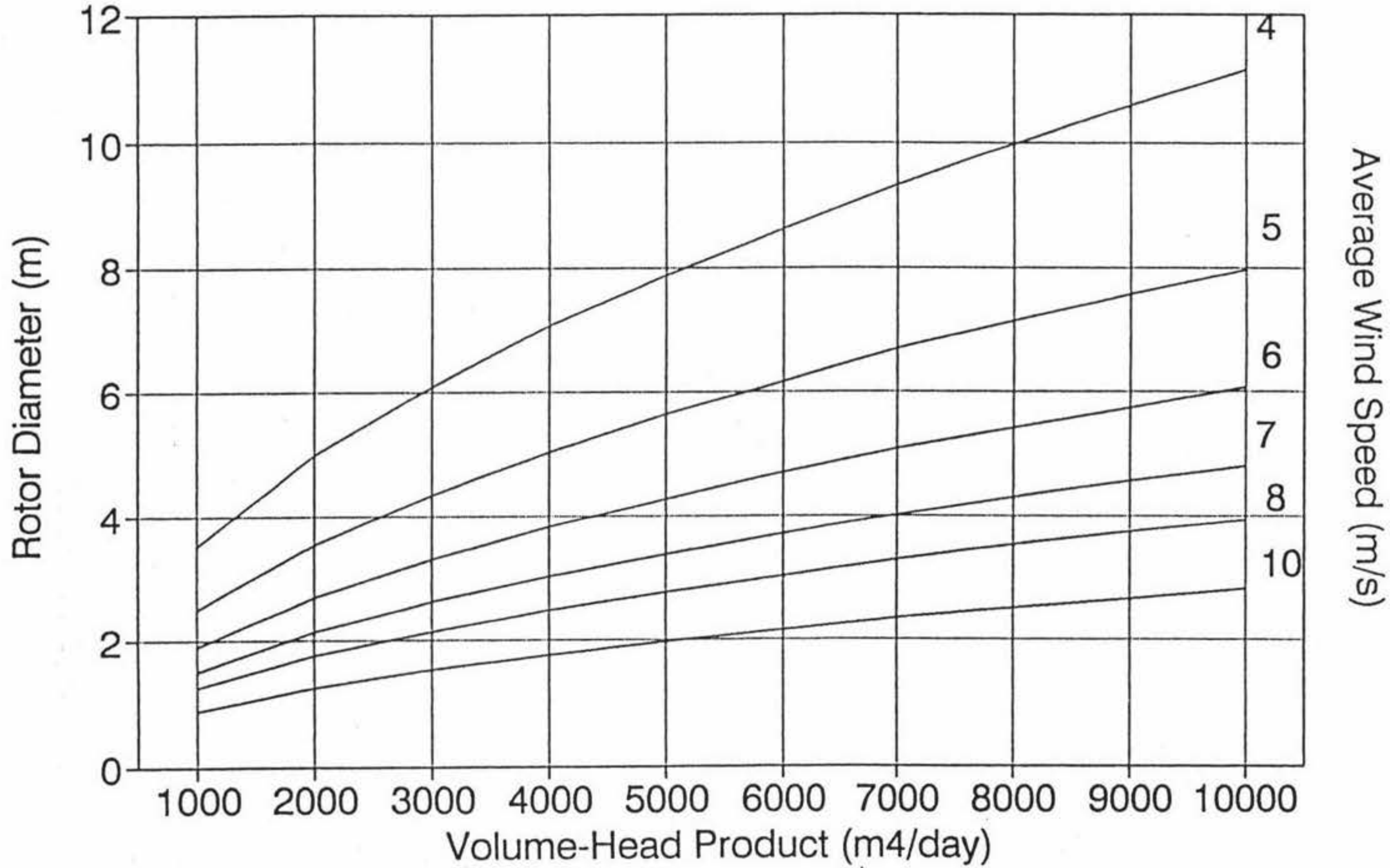


Figure 7.15 Nomogram for Sizing Wind Pump Rotor (EPF 2.8)

7.11.4 Basis of the Design Nomograms

Equation 7.6, from Lancashire et al (1987), for calculating the area requirement of a wind pump, was derived empirically from daily measurements on six wind pumps in Kenya,

$$A = \frac{1.14 \ x \ volume \ head \ product \ (m^4/day)}{Average \ Wind \ Speed \ Cubed(m/s)} \tag{7.6}$$

where A is the area of the wind pump rotor in m^2.

Working backwards from this equation, knowing the energy in the wind and the amount of energy required to lift a given volume of water, the author determined that the average overall efficiency of the six wind pumping systems examined in Kenya was 8%. Equation 7.6 was then modified for an overall efficiency of 10% This was then used to generate the information presented in the wind pump rotor nomograms.

Typically, piston pump systems have an efficiency of about 65% when used with a mechanical drive. Similarly, centrifugal pumps have an efficiency of about 50% for the pump and its connection to the wind turbine (Le Gourieres, 1982). If the pumps in Kenya did in fact have an efficiency of 65% this would indicate that the turbine efficiency associated with them was typically about 12% (0.65 x 12% ≈ 8%). This is consistent with an efficiency figure of 10% which has been suggested as a guideline figure for smaller turbines (Edwards, 1986).

7.11.5 Energy Pattern Factor

The Energy Pattern Factor (EPF) is the ratio of the actual power in the wind over that calculated from the average wind velocity value as presented by equation 7.7.

$$EPF = \frac{Power \ from \ the \ Velocity \ Distribution}{Power \ from \ the \ Average \ Velocity} \tag{7.7}$$

(Gipe, 1989)

The EPF is also a function of the shape factor used in the Weibull distribution. They are related in the way shown in table 7.9.

Table 7.9 Relationship between K and EPF

Shape Factor, k	EPF
1.5	2.8
1.8	2.2
2.0	1.9

It will be recalled that the Raleigh distribution corresponds to a shape factor of 2.

7.11.6 Example showing the use of the Rotor Sizing Nomograms:

This is assuming there was an average constant flow rate of 5 l/s and the total required head, calculated in the manner shown earlier in section 7.11.1, was 15 m. The average wind velocity was 6 m/s with a EPF of 1.9 (k = 2). Overall efficiency was 7%.

Step 1: The total pumping head (H) is determined

$$H = 15 \text{ m}$$

Step 2: The Volume-Head product is calculated

5 x 86.4 = 432 m^3 per day

(1 litre per sec = 86.4 m^3 per day)

432 x 15 m = 6480 m^4 per day.

Step 3: The overall system efficiency is determined

Efficiency = 7%

Step 4: The appropriate nomogram is used

After determining the average wind velocity and Energy Pattern Factor, the nomogram for an EPF of 1.9 is selected. 6480 m^4 is first located on the horizontal axis and then one moves vertically until the line corresponding to the average wind velocity is intersected. Moving left until the vertical axis is struck results in a rotor diameter reading of 6 m.

The correction factor corresponding to the overall efficiency of 7% according to table 7.8 is 1.2.

$$1.2 \times 6\ m = 7.2\ m.$$

Therefore the required rotor diameter for the above conditions is 7.2 m. This figure should be regarded as a minimum.

7.12 Determining the Pump Size

This is best left to the manufacturers to recommend. A small section, 2.19, in the literature review discusses this issue.

7.13 Determining the Storage Requirement

To do this information on the frequency of lulls each month, the duration of the longest lull likely to be experienced and the daily water requirement, is required. It has been suggested that in most locations a tank sized for 4 days storage would be adequate (Lancashire et al, 1987).

The required storage capacity (SC) can be approximated by using equation 7.8:

$$SC = \textit{Daily water requirement} \times \textit{longest lull} \times \textit{safety factor} \qquad (7.8)$$

The safety factor will depend on the economics of water storage and on the value of the water supply to the consumers or irrigators.

CHAPTER 8

MICRO-HYDRO

8.1 Introduction

Micro-hydro power is a more concentrated form of energy than either solar or wind power and therefore, when it is available, its use is favoured. The technology associated with it is well established although advances have been made which enable higher efficiencies and performance levels to be achieved.

This chapter examines the key design considerations in the design of a micro-hydro system. It begins with describing the process of calculating the power in the water, then examines different methods of quantifying the head and flow. It goes on to look at selecting the most appropriate type of turbine for a specific situation and then examines the process of determining the turbine design parameters for both Pelton and Crossflow turbines. It then also examines intakes and penstocks, energy storage both in dams and in batteries, and various factors associated with micro-hydro electric generators.

8.2 Calculating the Power in the Water

The amount of energy contained in the water is completely dependent on, and directly proportional to, the rate of water flow and on the fall (head) of that water. This can be calculated from the equation 8.1.

$$P = 9.81 \times H \times Q \tag{8.1}$$

where:

P = Power output of the turbine (kW)

Q = flow (m^3/s)

H = head (m)

(Martin, 1981)

Example: Suppose that from a stream 70 l/s is able to be diverted (1000 L= 1m^3). The fall able to be obtained is 6 m.

The power in the water is therefore:

$$9.81 \times 6 \text{ m} \times .07 \text{ m}^3 = 4.1 \text{ kW}$$

For Pelton wheels the conversion efficiency is about 90% (Dunn, 1986). Loss of efficiency from the transmission system, pipe friction, and efficiency of any attached pump or generator must also then be taken into account to obtain the overall system efficiency. Overall system efficiency for micro-hydro systems is often around 60% although lower head systems tend to be less efficient than higher ones (Sloan, 1979).

8.3 Determining the Flow Rate

It is believed that in Australia at least, the lack of available stream flow data is one of the major constraints to farm hydro power installations (Hinkley & Sturgess, 1990). The minimum expected flow rate for all the months of the year needs to be determined and compared to the power demand throughout the year to decide on the design flow rate.

Such factors as the topography, vegetation, geology and climate can in some instances be used as indicators of both reliability and of peak flow. Ideally flow rates are measured over a period of a year. Rainfall data can then be assessed to determine how much rain fell over the catchment area in comparison to other years. When flow rate is plotted against time a flow-duration curve is formed. This shows the percentage of time that a particular flow rate is exceeded (Hothersall, 1984).

During peak flooding it is the height to which the water level reaches rather than the flow which is of interest. A visit to the site shortly after these conditions can be useful for information on siting the turbine to ensure it is not swept away during flooding. This visual inspection should be combined with the local knowledge of the stream and its characteristics.

The most common methods for determining flow are as follows:

8.3.1 Container Method

This method is only really suitable for small streams or where all of the flow is able to be diverted into some container of known volume. The time taken to fill it is then measured from which an accurate assessment of the flow can be made. A small temporary dam may need to be built.

8.3.2 Float Method

This is a rather inaccurate method. A float is timed as it passes through a measured distance of the steam. The time can then be related to the flow once the width and depth of the stream are known. The following procedure for doing this is from Tamar Designs:

1. a board is marked at 0.5 m intervals and placed across the stream,
2. the depth of the stream is recorded at each mark,
3. the depth is multiplied by the width of the stream to obtain an average cross sectional area (m^2),
4. the area figure is multiplied by the velocity (m/s) that a float travels,
5. the figure derived from step 4 is multiplied by 0.83 to arrive at a flow rate in m^3/s (0.83 compensates for the differences in flow rate at different depths).

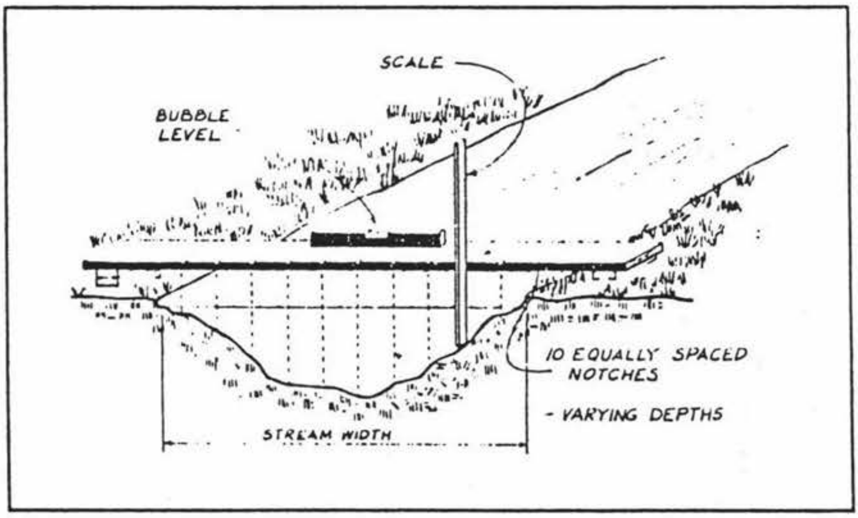


Figure 8.1 Measuring Flow with a Float (Ministry of Energy, 1986)

8.3.3 Weir Method

This is one of the most accurate methods. Two types of weirs are in common use: the V notch and the trapezoidal (Cipolletti) weir. The one which is most appropriate will depend on the flow. For small flows a V notch weir is best.

Table 8.1 Discharge Tables for Weirs

Discharge table for 90° triangular weir.*

Head over weir crest (mm)	*Discharge over weir* (m^3/hr)	(*litres/sec.*)
60	4.680	1.3
75	8.160	2.2
90	12.720	3.6
110	18.780	5.2
120	26.10	7.2
135	34.98	9.7
150	45.36	12.6
170	57.48	16.0
185	71.34	19.9
200	87.06	24.2
215	105.0	29.2
230	124.38	34.6
245	145.80	40.5
260	169.2	47.1
275	195.70	54.4
290	223.26	62.1
305	253.8	70.5
320	286.44	79.6
335	321.12	89.3
350	358.80	99.7
365	398.58	110.8
380	441.42	122.7

Discharge over Cipolletti weir for various lengths and heads.*

Head over weir crest	*Length of weir crest in metres* 0.300		0.600		0.900	
	Discharge over weir					
(*mm*)	(m^3/hr)	(*litres/sec*)	(m^3/hr)	(*litres/sec*)	(m^3/hr)	(*litres*
65	33.29	9.25	66.58	18.49	99 87	27
75	41.26	11.46	82.52	22.92	123.78	34
90	54.24	16.07	108.48	30.13	162.71	45
105			136.69	37.97	205.04	56
120			167.01	46.39	250.51	69
135			199.28	55.36	298.92	83
150			233.4	64 83	350 1	97
170			281.6	78.22	422.41	117
185			319.49	88.8	479.53	133
200			359.35	99.82	539.02	149
215			400.52	111.26	600.78	166
230					664 74	184
245					730.81	203
260					798.95	221
275					869.07	241
290					941.14	261
305					1015.1	281

*Formula used. $Q = 1.86\,BH^{1.5}$
where Q is in m^3/s and B & H are in metres.

(MAF Aglink, AST 60/2)

For a weir to be accurate it must be constructed to certain design specifications as outlined below:

1. the weir must be at right angles to the flow and large enough to take the whole flow,
2. the weir notch must be horizontal,
3. the height of the weir above the upstream bed should be at three times the maximum head over the weir crest,
4. the weir should be high enough to allow water to fall freely to the downstream flow level,
5. water upstream of the weir should be in a tranquil state and its velocity should not exceed 0.51 m/s,
6. the staff gauge to measure the depth of water flowing over the crest should be installed at least 1.2 m upstream of the weir,

7. the edge of the crest of the weir should be sharp,
8. for a Cipolletti weir the depth of flow over the crest should be no more than one third of the width of the length of the crest,
9. for the V notch weir the notch is to be a right angle.

(MAF Aglink, AST 60/2)

One way to measure the depth of flow over the weir is by driving a peg into the stream bed where you want to take the measurement. It should be knocked down until its top is level with the bottom of the notch. The ruler or staff gauge can now be placed directly onto this when readings need to be taken (Harrison-Smith, 1985).

8.3.4 Salt Dilution Method

Salt dilution gauging has been found to be a very simple and accurate method (within 5%) for measuring flow, especially of small turbulent rivers. The method consists of injecting a known quantity of salt into the river and monitoring the conductivity of the river at a point down stream as the cloud of salt solution flows past (Holland, 1986).

8.3.5 Using Catchment Area Data

A thesis by Hothersall (1984) demonstrated this method. It is based on the fact that some water falling in a particular catchment evaporates and some is lost to transpiration. The average annual runoff for a particular area is assessed by calculating the difference between the average annual rainfall and the average annual evapotranspiration.

While appearing to be helpful for a Papua New Guinea context, it is the opinion of this author that because no account is taken for infiltration and deep percolation, it would have little application for assessing sites for micro-hydro potential in New Zealand.

8.4 Measuring the Head

Accuracy is most important where there is limited head available head, that is less than seven or eight metres (Ministry of Energy, 1986). The most appropriate method to determine the head will depend on the degree of accuracy required.

8.4.1 Using a Surveyor's Level

This is one of the most accurate ways and is depicted by figure 8.2. A surveyor's level or level on a camera tripod can be used to sight from peg top to peg top. A helper marks the pole directly on the line of sight. The total head is then the sum of the measurements (A, B, C, D).

8.4.2 Spirit Level

A carpenter's spirit level can be used in situations where the degree of accuracy required is not high. To use a spirit level in this way, a piece of tin or some reflector needs to be placed on it so that the levelling bubble is visible while siting along the level. The first sighting should be taken while standing downstream from the intake point and sighting to the probable intake location.

The next measurement is made by swivelling around and sighting a tape measure being held up by an assistant at about the point where the turbine is to be located. The measurement from the water level where the assistant is, to the point on the tape measure that corresponds to the line of site, is the head. This can be done in stages if necessary (Harrison-Smith, 1985).

8.4.3 Using a Hose and Pressure Gauge

Another method, albeit a less accurate one, is to use a length of hose with a pressure gauge at the end. The open end of the hose is inserted into the water source and pressure is measured at the other end with the gauge. This is continued until the proposed turbine location is reached. All of the readings are then added together.

To assist in using this technique the following conversion factors may be used:

1 psi = 0.704 m

1 kPa = 0.102 m

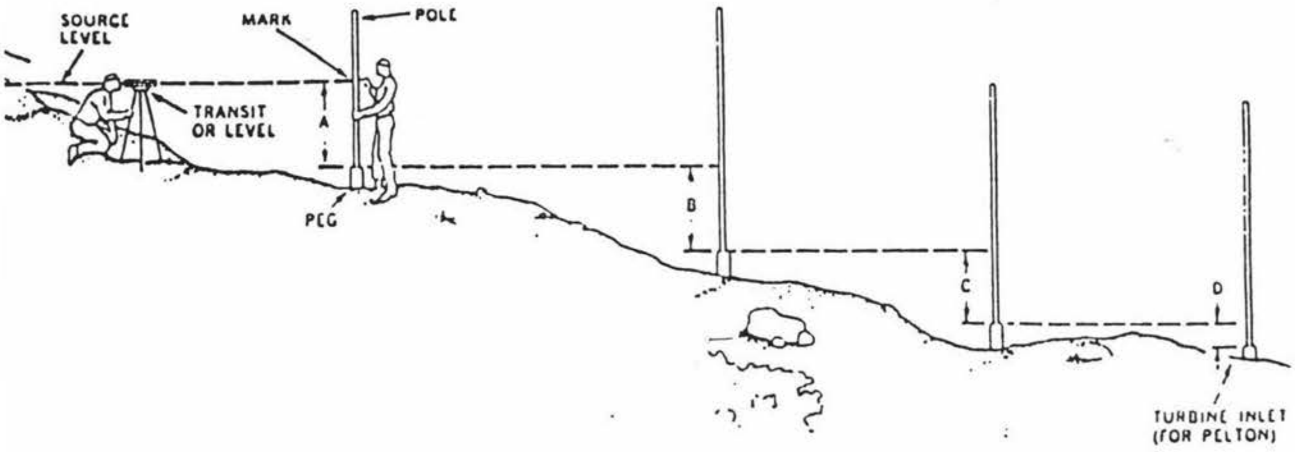


Figure 8.2 Measuring Head using Surveying Equipment (Tamar Designs)

8.4.4 Using an Aneroid

Preliminary head measurements can be made using an aneroid but these should always be verified before a final decision is made unless it is a particularly high head installation. Just as with any aneroid survey, two instruments need to be used. One remains at 'base', while the other is used to take readings at various locations. The base aneroid is then used to adjust the readings of the other to take account of the changes in atmospheric pressure during that time.

8.4.5 Adjusting Gross Head to Obtain Net Head

It is important to distinguish between 'gross head' and 'net head'. Gross head is the vertical height from the tail water level to the intake level. Net head is the head actually available to drive the turbine at full load. Net head takes into account all associated losses such as pipe friction and the rise in the tail water level. With an impulse turbine the distance of the jet above the tail water level must also be deducted.

Because reaction turbines often employ draft tubes to increase the effective head, for these turbines, the distance to the surface of the water at the expected point of <u>discharge</u> is taken as the effective head.

8.5 Other Factors to Consider in Site Selection

Although head and flow are the most important influences on the amount of power which is able to be produced other factors also need be considered when assessing the suitability of a site for a micro-hydro installation.

These include the following:

1. flow throughout the year,
2. power demand throughout the year,
3. length of pipe required to obtain a certain head (the longer the pipe the more friction losses will be associated with it),
4. water conditions,
5. soil conditions,
6. minimum tail water elevation,
7. area of pond above dam (if a dam is required),
8. depth of the pond,
9. distance from power plant to where electricity is required.

(Adapted from Halacy, 1977)

8.6 Selecting the most Appropriate Turbine

All large scale electricity generation today uses one of three types of turbines, namely Pelton, Francis or Kaplan. All of these have a very high efficiency of about 90% or more. Cross flow turbines and multi-jet Pelton wheels are often used for micro-hydro systems in remote areas because they are suitable for a wide range of site conditions and power outputs. This is especially so because they normally use a belt or gearbox drive as speed increasers to extend the useful head and power range.

Section 2.33 in the literature review examines the merits and disadvantages associated with various types of turbines. Figure 8.4 on a following page, adapted from Dakers and Martin (1982), enables the optimum type of water turbine to be selected for conditions of up to 15 m head and 200 l/s flow. It shows the wide applicability of the cross-flow turbine. For conditions of higher flow, figure 8.3 can be used.

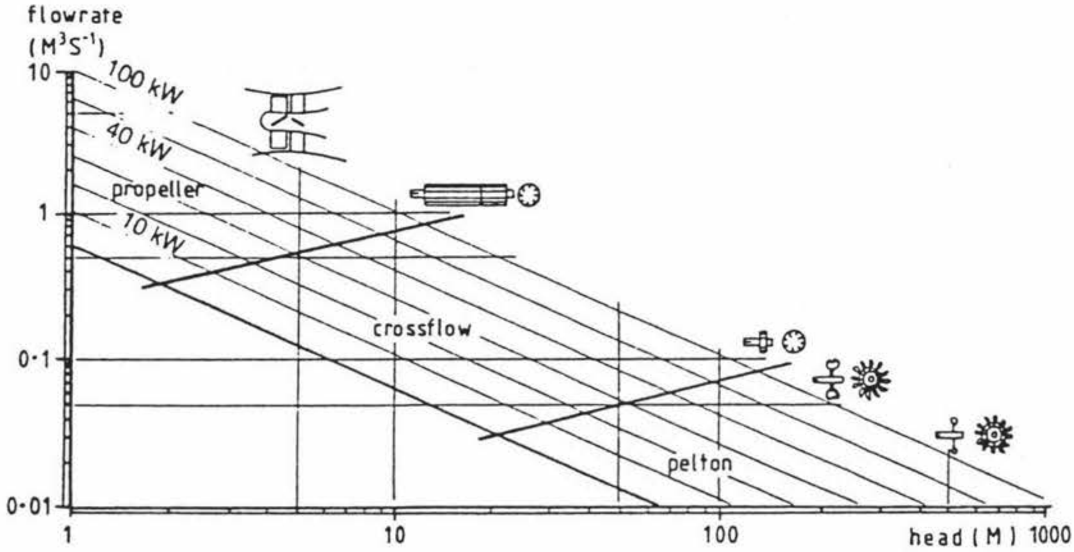


Figure 8.3 Turbine Selection Chart for Relatively High Flows (Adapted from Hothersal, 1984)

Selection of the most appropriate type of water turbine will involve consideration of a number of other factors such as: cost; part flow efficiency; resistance to silt abrasion; and type of control system to be used (Holland, 1986). Figure 8.9 illustrates the part flow efficiency of turbines. Because of the simplicity of their manufacture, Pelton wheels and Crossflow turbines are very commonly used. Pelton wheels tend to be used for high heads and Crossflow turbines for high flows. These two turbines are therefore concentrated on in this section. Running centrifugal pumps in reverse is also examined.

8.7 Pelton Wheel

Where the wheel is either stationary or the buckets travel at the same speed as the water then no work will be done and the efficiency will be zero. If the bucket velocity is selected as half that of the jet, the jet will in theory leave the bucket with a velocity of near zero and so have transferred practically all of its kinetic energy to the bucket.

In the design of a Pelton wheel two parameters are of particular importance: the ratio of the bucket width to the jet diameter; and the ratio of the wheel diameter to the jet diameter. These parameters are illustrated in figure 8.5 (from MAF Aglink, AST 65/7). The former value is optimised at 4 to 5, while the latter has in practice a minimum value of about 10 (Massey, 1970).

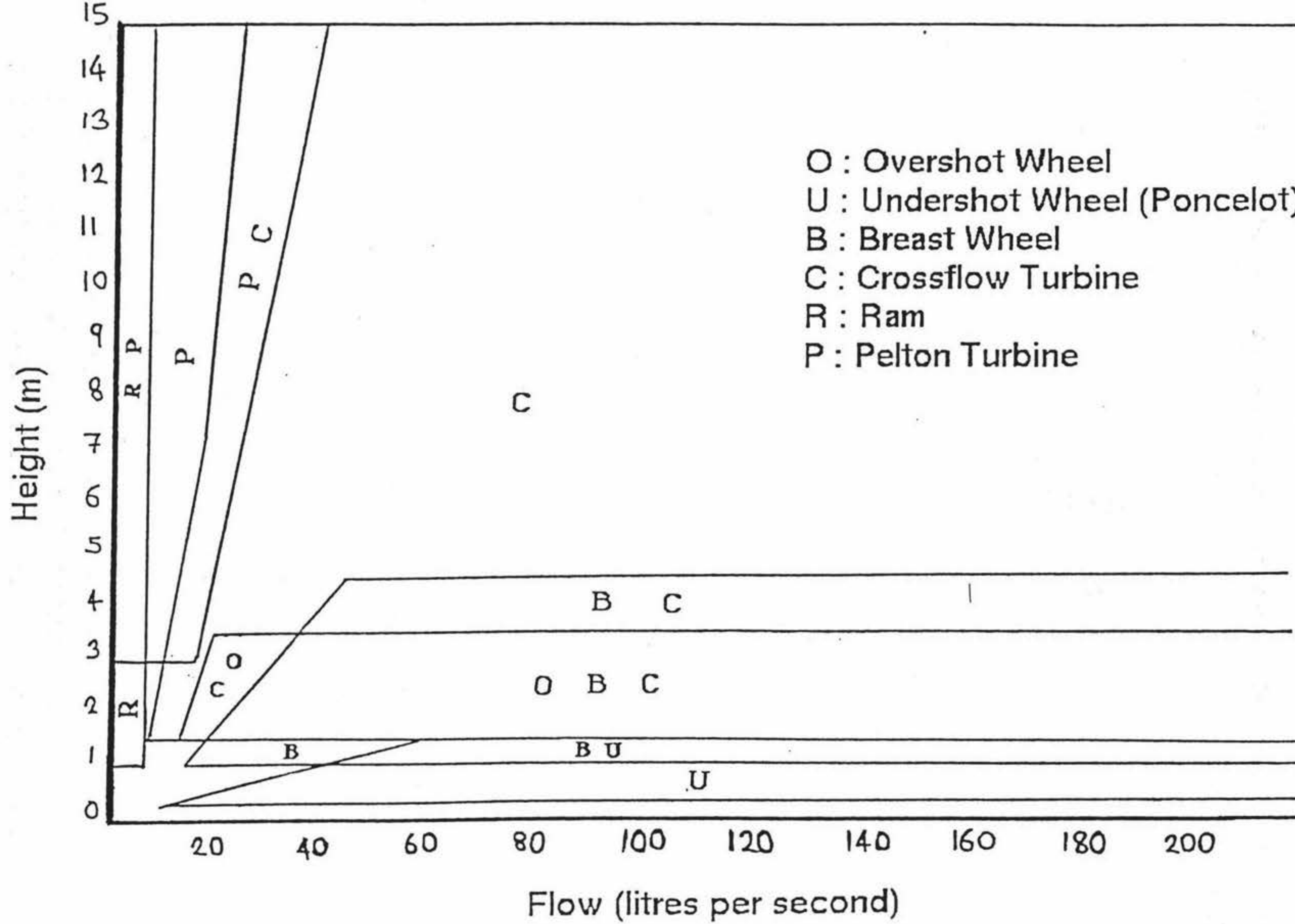


Figure 8.4 Turbine Selection Chart (adapted from Dakers & Martin, 1982)

8.7.1 Specific Speed

The specific speed, n_w is used to express the region in which a turbine will operate. It is given by the equation 8.2:

$$n_w = \frac{N\sqrt{P_s}}{H_t \frac{5}{4}} \qquad (8.2)$$

where:

n_w is the specific speed of the wheel

N is the wheel speed (rpm)

P_s is power (kW) given by equation 8.1

H_t is head (m)

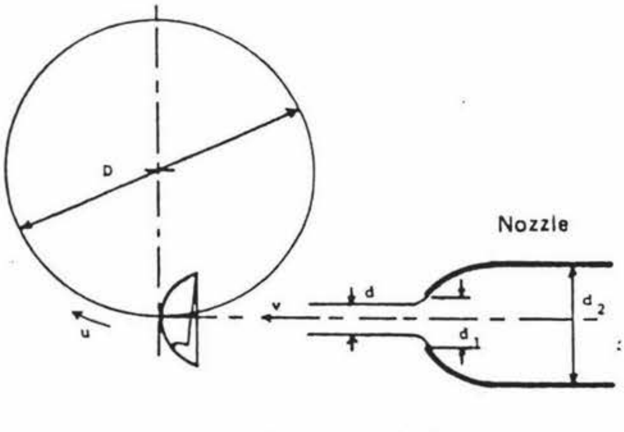


Figure 8.5 Pelton Wheel Design Parameters (MAF Aglink, AST 65/7)

If the number of jets is N_j then the specific speed per jet (n_s) is given by equation 8.3. To obtain maximum efficiency the specific speed per jet should be 18 - 25 for H_t less than 300 m. Therefore for 3 jets the optimum specific speed would be 25 x √3 = 43.3 (MAF Aglink, AST 65/7). The specific speed characteristics can then be used to determine the ratio of the wheel diameter to the jet diameter, and the number of buckets by using figure 8.6.

$$n_s = \frac{n_w}{\sqrt{N_J}} \qquad (8.3)$$

The parameters of the number of jets, the jet diameter, and the jet velocity will all affect the amount of power delivered to the shaft according to the following equation 8.4:

$$P = 0.368 \ x \ no.\ of\ jets \ x \ d^2 \ x \ v^3 \ x \ e \qquad (8.4)$$

where:

P = power output of the turbine in kW

d = jet diameter in m

v = jet velocity in m/s

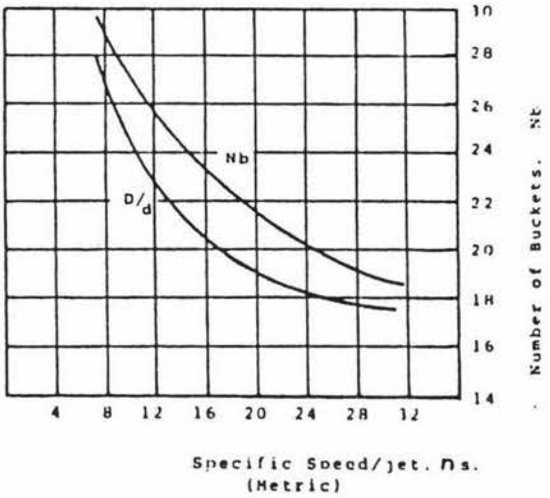


Figure 8.6 Specific Speed Relating to Number of Buckets (reproduced from MAF Aglink, AST 65/7)

Because blade speed is directly proportional to the jet speed it can be seen that the power is directly proportional to the cube of the jet speed - just as is the case with wind power. However, as already mentioned, power is maximised where the speed of the buckets is half that of the jet. Figure 8.7, from Massey (1970), illustrates the effect on turbine efficiency when this is not the case. V_1 represents the velocity of the jet and U represents the velocity of the buckets.

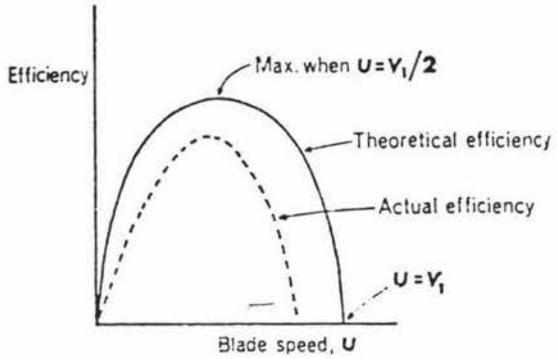


Figure 8.7 Relationship between Blade Speed and Efficiency (Massey, 1970)

8.8 Crossflow Turbine

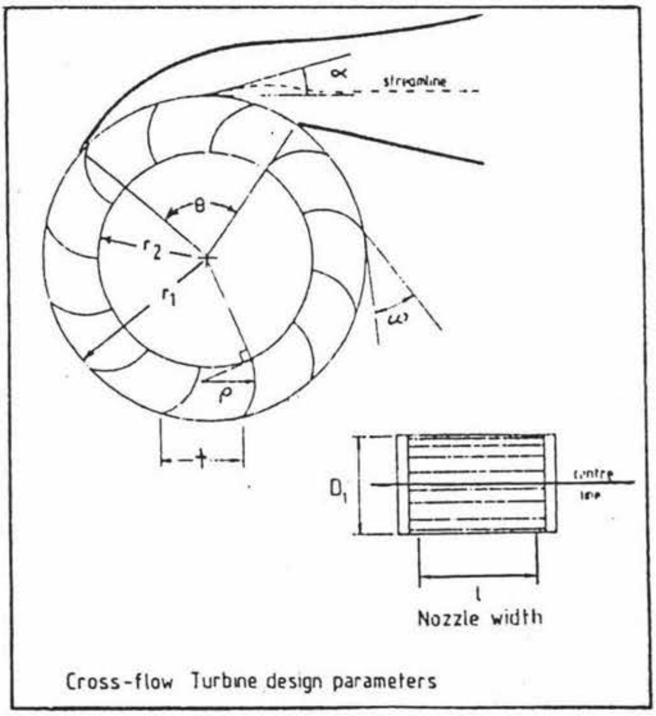


Figure 8.8 Crossflow Turbine Design Parameters (Dakers and Martin, 1982)

The Crossflow turbine design parameters are illustrated in figure 8.8.

The design variables for the runner are:

r_1: runner radius
r_2: blade depth
ω: blade orientation
ρ: blade radius of curvature
t: blade spacing
runner width
surface roughness of the blades
shape of the blades leading edge.

The design variables for the nozzle are :

α: angle of entry
θ: subtended angle
L: nozzle width
surface roughness
shape

The following runner parameters are recommended values as determined by Mockmore et al (1949) and Haimerl (1960), while the following nozzle parameters are those recommended by Dakers and Martin (1982).

$\rho = 0.33\ r_1$
$r_2 = 0.67\ r_1$
$t = .35\ r_1$
$\omega = 30°$
$\alpha = 16°$
$r_1 = 158$ mm
$\theta = 69°$

The nozzle width, L, varies according to the flow (Q) and the total input head (H_t) according to equation 8.5:

$$L = \frac{4.47\ Q}{H_t^{0.5}} \tag{8.5}$$

where:

H_t and L are in metres

Q is in m^3

H_t is the total head measured to the bottom of the runner

The speed of the turbine in rpm at maximum efficiency is given by n in equation 8.6 from Dakers and Martin (1981):

$$n = 140\ (H_t)^{0.5} \tag{8.6}$$

These recommendations apply up to a nozzle width, L, of 300 mm.

8.9 Using Centrifugal Pumps as Turbines

For centrifugal pumps to operate as turbines they must be run in reverse mode. The idea is attractive because of the ready availability of such pumps and their replacement parts, and the fact that such a system may cost as little as half a conventional turbine. Hline and Wibulswas (1987), examined the feasibility of using small centrifugal pumps as turbines and concluded that it was both technically and economically feasible.

Eckard, in his article entitled 'The development of reversed centrifugal pumps for hydropower' provided the following design procedures:

Step 1: The required pump size needs to be determined assuming that the pump size is characterised by the discharge diameter (assume K = 300 for first attempt)

$$Pump\ Discharge\ Diameter,\ d = \sqrt{\frac{Kq}{\sqrt{h}}} \tag{8.7}$$

where:

q is the available flow of the water (m^3/h)

K is an empirical constant to calculate pump size when operating as a turbine

h is the available head of the water

Step 2: The pump model with the smallest standard impeller needs to be chosen

Step 3: The performance curve of the chosen pump model is read at 1,400 rpm to determine the specific speed, N_s (Q and H of the pump at the peak efficiency point)

$$N_s = \frac{n\sqrt{Q}}{60\,H^{3/4}} \tag{8.8}$$

where:

N_s is the specific speed of the pump

n is the speed of the pump in rpm

Q is the flow at which the pump operates at peak efficiency at 1,400 rpm (m^3/h)

H is the head at which the pump operates at peak efficiency at 1,400 rpm (m)

Step 4: From the following table 8.2 the value of the constant 'K' is determined. This step is repeated bearing in mind that the velocity of the water through the discharge flange of the pump with flow 'Q' should not exceed 8 m/s.

Table 8.2 Constants versus Specific Speed in the Determination of Pumps Operating as Turbines

N_s	10	20	30	40	50*
K	320	280	250	210	190*
Z	0.60	0.70	0.80	0.95	1.05*

* Based on field observations only. No laboratory tests were performed to determine the constants of pumps with specific speeds in excess of 40

[1] Variables described elsewhere

Step 5: Using the following equation 8.9, the speed at which this chosen pump must operate to give optimum efficiency and power when used in reverse as a turbine, may be calculated

$$N = \frac{85000\ Z\sqrt{h}}{D} \qquad (8.9)$$

where:

D is the discharge flange diameter (mm) of the pump operating as a turbine

Z is an empirically derived constant to calculate required pump speed when operating as turbine

N is the speed at which the chosen pump should operate as a turbine (rpm)

If the resulting speed is in excess of 3,000 rpm the pump model with the next largest impeller size should be selected and then steps 1 to 5 repeated. Preference should be given to pumps with higher specific speeds (Eckard, year unknown).

Care does needs to be taken to ensure that the flow rate through the pump discharge flange is limited to 8 m^3/hour, that the speed is limited to 3,000 rpm, and that the pump manufacturer's power to speed ratio is adhered to. Where manufacturer's performance data is available for pumps operating in the turbine mode this should be used in preference to the above method.

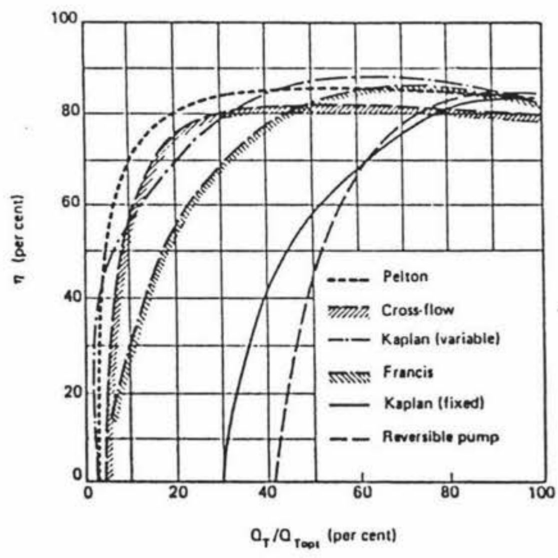


Figure 8.9 The Relative Performance of Turbines Measured Against Percentage of Design Flow (Engeda & Rautenberg, 1988)

The efficiency of pumps operating in reverse as turbines can be almost identical to their efficiency of water pumping. They do ,however, have a poor part load efficiency (Engeda & Rautenberg, 1988). The is illustrated by the efficiency comparison, in figure 8.9, of various turbine types with a reverse running pump.

Ideally cavitation properties of the pump, when running in the reverse mode, should also be examined. Mechanical seals are preferred to packed seals, as a clean supply of gland sealing water is unlikely to be available (Giddens, 1986).

8.9.1 Disadvantages of Using Pumps as Turbines

One of the main disadvantages of running pumps in reverse as turbines is that they have a poor part load efficiency in comparison with conventional turbines of the same size. Another disadvantage is that there is a lack of operating characteristics known for pumps over a range of specific speeds. The performance of such a system is therefore difficult to predict.

The turbine performance prediction cannot be based on the pump's specific speed, or on the turbine specific speed of the machine, because it is not necessarily the optimum turbine design for the specific speed. Reverse running pumps also have a limited efficiency and a reduced operating range (Engeda & Rautenberg, 1988). Despite their poor part flow characteristics they are worth considering especially under guaranteed full flow conditions (Holland, 1986).

8.10 Intakes

Intakes are used for transferring water from the water course or dam into a pipe. The intake needs to be placed at sufficient depth beneath the water surface to avoid the formation of vortexes which would allow air to be sucked into the system. It is important to have some way of keeping out objects, which could damage the turbine or prevent water hammer, if they were to become suddenly lodged in the intake.

The type of intake required is decided on the basis of the site geometry, a sampling of the bed material and the required extraction rate (Giddens, 1986). Where the flow warrants the use of steel bars their spacing should be carefully considered. If too close, trash will quickly accumulate and frequent cleaning will be required. Conversely, if the spacing is too wide there is a risk of damage and blockage of the turbine runner blades. Some intake designs are virtually self-cleaning.

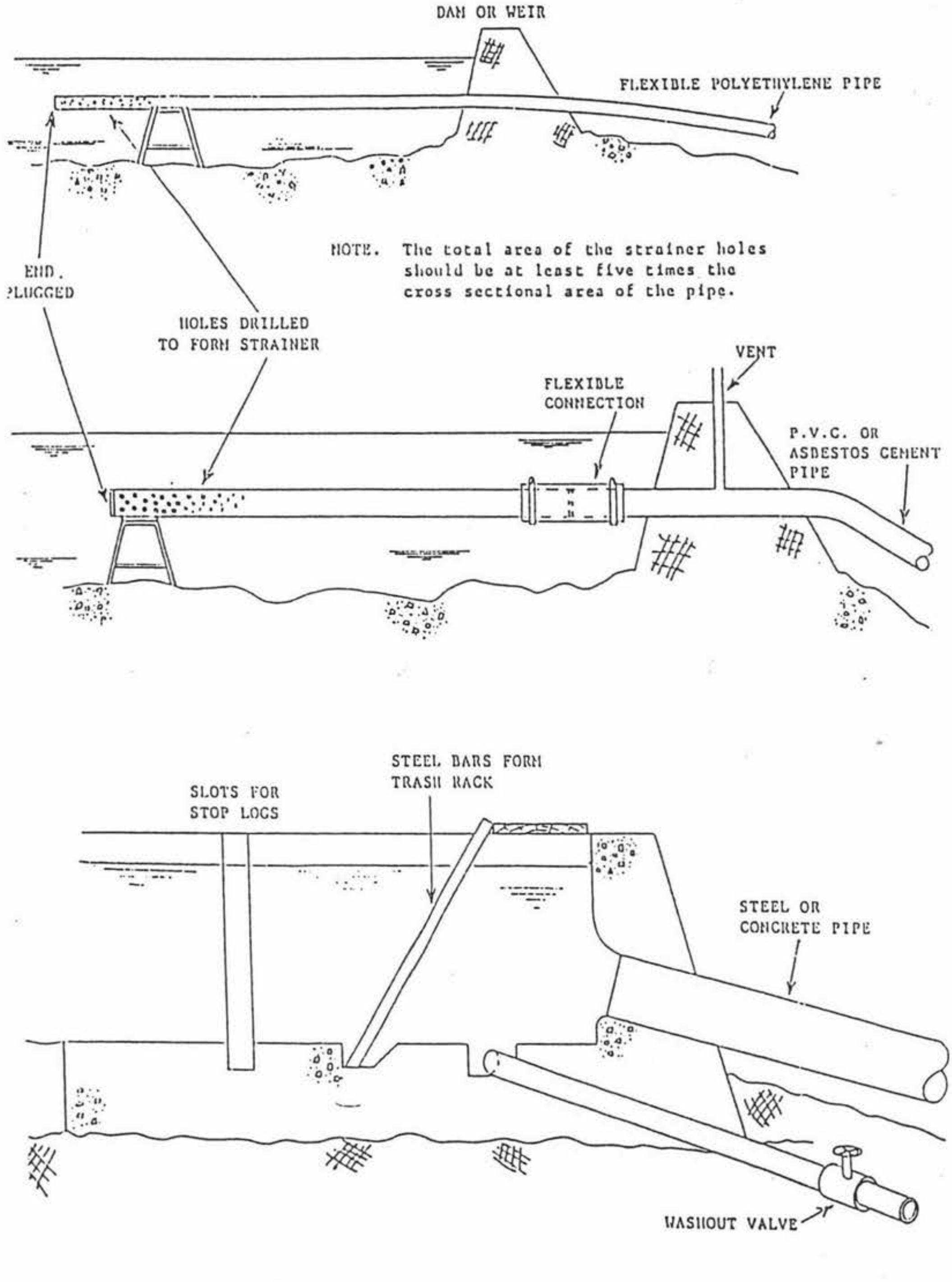


Figure 8.10 Suggested Intake Structures (Tamar Designs)

Various types of intake systems are illustrated in figure 8.10. Note the third diagram which has the facility to drain the dam thereby making cleaning out of accumulated silt considerably easier. An intake suitable for mountain streams carrying only small gravel bedload has been developed by the University of Canterbury. It has operated with no maintenance for a number of seasons. This is illustrated in figure 8.11.

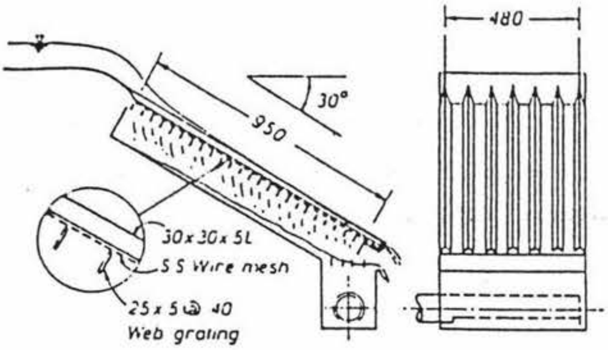


Figure 8.11 An Intake Suitable for Mountain Streams (Giddens, 1986)

8.10.1 Venting

In the event of a major blockage occurring, a vent prevents the formation of a vacuum which could potentially collapse the intake. It should be positioned below the intake and above the pond level (Carson, 1990).

8.11 Penstocks

The penstock pipes deliver the water from the intake to the turbine. Occasionally a headrace might be used to minimise the length of the penstock required. Penstocks generally follow the surface topography although they may run in a shallow trench for protection (Giddens, 1986).

8.11.1 Determining Required Pipe Size for Penstock

Using the pipe headloss tables (table 7.7) the friction loss for a given pipe with a given flow over a certain distance may be determined. When making a preliminary feasibility study it is normal to allow for up to about 10% of head to be lost in pipe friction (Tamar Designs). The penstock cost is often substantial so its diameter needs to be minimised while ensuring it is not causing excessive head loss due to friction (Carson, 1990).

Where PVC pipe is used, it is best to bury it so it is protected from stock and the sun's rays which cause the walls to weaken.

8.11.2 Hydraulic Gradient

The hydraulic gradient for each system must be taken into account for the system design. This is an imaginary line which represents the height along the pipeline at which the pressure reduces to zero. If at any point the pipe is above this line then a partial vacuum develops in the pipe. This situation is to be avoided as it can cause gas bubbles to form in the pipe which reduces the efficiency of the turbine (Carson, 1990).

8.11.3 Water Hammer

Care should be taken to avoid water hammer. Gauges can be installed so that pressure can be monitored. To avoid rapid closure of valves they should not be of the butterfly type which can completely close the pipe with half a turn.

8.12 Energy Storage in Dams

Where the power supply does vary significantly over time, which is normally only seasonally for micro-hydro systems, dams can be used to store water (and its associated potential energy) during periods of surplus flow for times when flow is insufficient. The common types are shown below:

1. **Earth Fill** (Exide Battery Specifier's Manual).
2. **Concrete**. These tend to be expensive but permanent. In some situations it may be used in combination with earth fill.
3. **Timber Frame**
4. **Gabion**. These are made of wire baskets filled with rocks.

All dams need a spillway which will safely pass extra water. The exception is a flow-through type of dam covered in coarse rock on top (Carson, 1990).

8.13 Battery Storage

With micro-hydro systems the output (power supply) tends to be reasonably constant, especially on a daily basis. This contrasts strongly with the very marked variations of photovoltaic systems. Wind power systems typically are somewhere in between. Because of this batteries are not used to smooth out the variations in power supply of micro-hydro systems, but rather the variations in power demand.

As is described in section 5.2, the difference between the peak demand and the average demand can often be about 2,000%. This means that if no storage is used the system would need to be 20 times larger than if the peak demand could be spread out throughout the day, assuming no efficiency losses. If the system was sized to meet only the average demand the peak demand could in theory still be met using batteries. Clearly both of these options are impractical and so either the peak load needs to be reduced or some storage needs to be employed, or preferably both.

Where a system is being designed, the various combinations of system size and storage capacity between the above two extremes need to be assessed. In many instances the output of a potential micro-hydro will be limited by the particular site's characteristics (eg. minimum flow).

8.14 Legal Issues

It is important that the legal requirements of the country and area in which the dams are to be constructed are met. Often a water right needs to be obtained and in some cases a design certificate for the dam, depending on its size.

8.15 Micro-Hydro Electric Generators

Figure 8.12 and Figure 8.13 on the following pages show the overall lay out of a commercially available 'Ecowatt' Pelton wheel and Crossflow respectively.

Synchronous generators are almost always used on isolated micro-hydro plants, as opposed to induction generators (Dunn, 1986). The average synchronous generator has an efficiency of about 90% to 95% (Gaynor, 1985). There are cheap but effective units available developed originally for the small diesel generator market (Holland, 1986). Direct current (DC) generators are still sometimes used for smaller systems generally under 1 kW .

Induction generators are essentially induction motors run in the reverse mode. Their main disadvantage is that they require some form of external excitation to operate (Inversin, 1986). The University of Auckland was (in 1986) undertaking research to solve the associated problems of excitation and voltage control (Giddens, 1986). Another major disadvantage of these types of generators is that they require a constant speed drive (McGuigan, 1978).

A generator coupled to a turbine and associated electrical equipment is often supplied as a complete package so care should be taken to ensure the supplier is aware of all of the requirements and specifications (Inversin, 1986).

8.15.1 Governing Systems

Governing has been defined as the ability of a machine to accept changes in load without large changes in speed and to maintain speed without 'hunting' when faced with a constant load (Liew, 1985). The reason that this is important is that frequency and voltage are both directly related to the turbine speed.

Three basic types of governing systems are available:

1. varying the water flow,
2. deflecting surplus water away from the turbine wheel,
3. using an electronic load control governor and operating the turbine at constant flow.

(Liew, 1985)

Electronic load control governors (option 3) are now widely used and generally considered the most appropriate form of speed control for micro-hydro plants (Holland, 1986). This is particularly where there is no storage facility, as it is both simpler and cheaper (Liew, 1985). It requires an inexpensive, load diverting governor which controls the frequency by managing the electrical power consumption. This enables operation of the turbine at a constant load (Giddens, 1986).

The electronic governor measures the consumer load and then adds to it a secondary load so that the total power load is always maintained at a constant (Liew, 1985; Robinson, 1988). These devices are very similar to voltage regulators used on cars to prevent batteries from overcharging (McGuigan, 1978). This type of governor can be located at any point in the system but is preferably situated close to the consumer so it is easier to use the 'dumped' energy.

Auckland University has developed such a governor which adjusts the load in 15 steps from no-load to full-load on the basis of a frequency range of 49.3 to 50.7 Hz. It can be used for any load up to 15 kW although it can also be used in multiples for larger loads (Giddens, 1986).

The most convenient signal for these devices to read is frequency. However where close frequency control is not essential voltage can be monitored instead. This is possible because voltage is related to generator speed and therefore frequency (Inversin, 1986).

8.15.2 Generator Speed

When a generator is purchased separately from the turbine it is important to specify the speed at which it will operate and its output frequency. The speed of the generator is related to the number of generator poles and the required frequency output in the equation 8.10. Micro-hydro systems tend to have two or four poles. Because those with four poles run at a lower speed they tend to be used more often as less gearing up from the turbine is required.

$$N = \frac{120\,f}{n} \tag{8.10}$$

where:
N = generator speed in revs/min
f = output frequency (Hz)
n = number of poles

(Inversin, 1986)

8.15.3 Brakes

Micro-hydro systems do not needs brakes per se however they do need to be carefully regulated with regard to their speed and their load. Governors regulate the flow of water to the turbine and so influence its speed. This is a particularly important function with electrical systems so that the correct frequency is achieved.

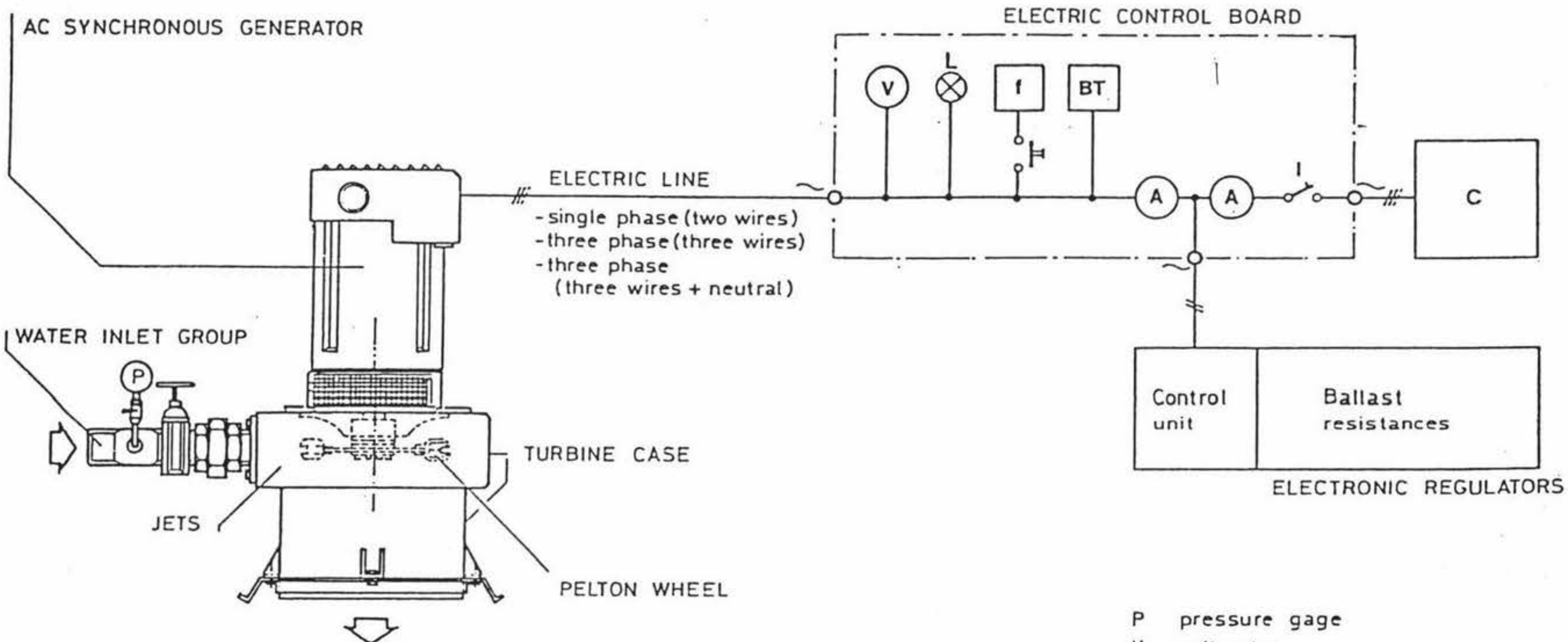
Pelton wheels turbines often incorporate some device which deflects the water away from the turbine when the load is removed. Sleeves can be fitted to the turbine which at the normal operating speed leave the flow largely unaffected. At higher than normal speeds, however, it reduces the efficiency and power output to the runner by deflecting water back on to the buckets and so applying a back pressure (Inversin, 1986).

8.15.4 Power Transmission

Belts are the most common form of transmission for small water power plants. V belts can attain efficiencies in excess of 97%! (McGuigan, 1978). It is preferable to avoid geared drives because they tend to be more complex and less reliable than belt drives.

Considerable variation in the possible wheel diameter means the designer is able to produce a turbine with a considerable range of rpm for the same net head. This becomes important if one wishes to run an alternator with direct drive, although the use of belts is more common with small micro-hydro systems (Harrison-Smith, 1985).

Pelton Wheel Electricity Generating System



P pressure gage
V voltmeter
A ammeter
f frequency-meter
L pilot lamp
BT under/over voltage alarm
I circuit breaker
C electric load

Figure 8.12 Pelton Wheel Electricity Generating System (adapted from 'Ecowatt' product manual)

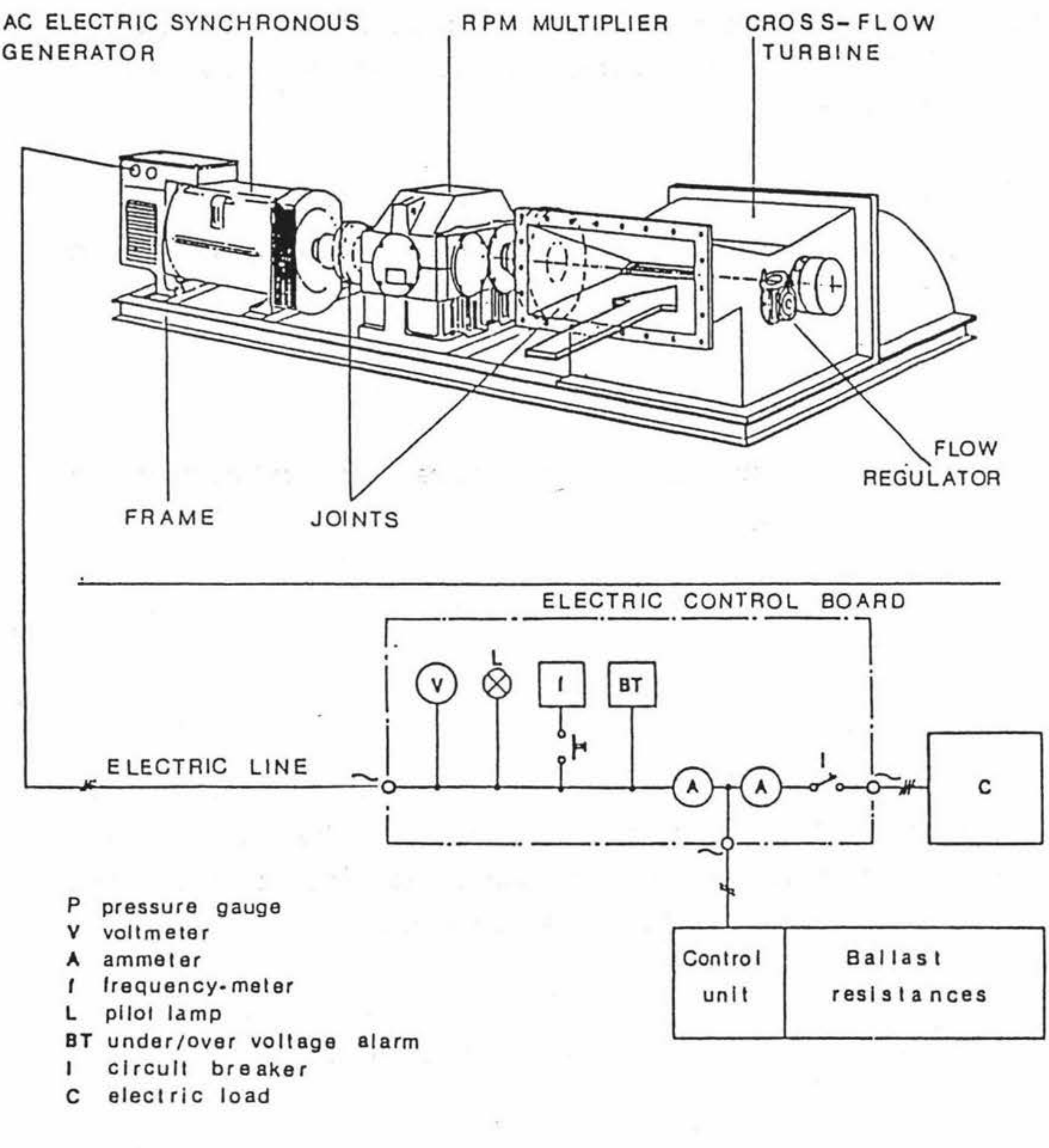


Figure 8.13 Crossflow Turbine Electricity Generating System (adapted from the 'Ecowatt' product manual)

8.16 Developing Country Applications

Micro-hydro is a low cost technology which can, through the provision of power, help create industries and employment in developing countries. Any technology introduced into a developing country must be appropriate if it is to be of long term benefit. Capital is often a major constraint while reliability, maintainability and simplicity are paramount. Education in the new technology is vital to ensure that the necessary skills are developed to operate and maintain the system and to ensure that there is an awareness of the hazards and limitations of it. Engineers are not generally trained in this area and so increased cooperation between them and social scientists is recommended (Giddens, 1986).

Meier and Arter (1989), in their article entitled 'Solving problems of micro-hydro development in Nepal', made the following recommendations:

1. all activity should be carried out in collaboration with a motivated local partner,
2. learning by doing is a good approach,
3. it is best to start with simple projects such as mechanical applications for the first experience of direct driving,
4. impact monitoring after the plant has gone into operation is essential,
5. those becoming involved in hydropower development must aim at long term activities.

8.17 Computer Programme

A shareware computer programme[11] called 'Hydrohelper' has recently been developed by American programmer, Art Carson. This program is intended to provide quick estimates of various parameters associated with small hydroelectric power systems and is useful for evaluating proposed systems or doing simple evaluations of their performance.

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[11] 'Hydro-helper' can be obtained by writing to the address below enclosing a US$25.

Small Hydroelectric Systems & Equipment Inc.
5141 Wickersham Road
Acme, WA 98220 U.S.A.

rnatively write to this author care of the Agricultural Engineering Dept, Massey 'ersity, New Zealand, enclosing NZ$40.

CHAPTER 9

HYBRID SYSTEMS

9.1 Introduction

Hybrid power systems incorporate more than one type of energy generating method. Often they blend the advantages of inexhaustible natural energy forms with the more traditional energy forms able to supply energy on-demand. The main advantage of hybrid systems is that often a more continuous power output is able to be maintained than from a single renewable energy source.

A careful analysis must be made of the proportions of energy generated by various forms with respect to the cost of that energy. This also needs to be linked to the demand profile (the energy demand fluctuations of the application). If a good match can be made between load and supply then substantial reductions in the cost of power can be achieved (Ministry of Energy, 1986). The aim of using hybrid systems is to reduce the overall cost of a system while not sacrificing the reliability of the energy supply.

This chapter limits itself to hybrid combinations of wind, photovoltaic and diesel generator systems. It begins with an overview of a wind-photovoltaic hybrid. It then goes on to look at diesel generators with respect to their disadvantages and fuel efficiency. Operating diesel generators with batteries is examined in section 9.4, which also considers design considerations for sizing the battery storage. Section 9.5 examines the advantages of wind-diesel systems and looks at the types of generators commonly used. Issues of control with respect to hybrid systems are then addressed in section 9.6.

Sizing the battery bank associated with a renewable energy hybrid system is discussed in section 9.7 and a procedure given. The final section examines the issue of sizing the different components associated with hybrid systems and provides an example of this for a wind-photovoltaic hybrid system. This example draws on various design tables provided in this study.

9.2 The Variable Nature of Renewable Energies in Relation to the LOLP

Because of the inherently variable nature of renewable energy, it is not economically feasible to design a system, albeit a hybrid system, which is completely based around renewable energy and which will be able to meet the demand 100% of the time. For this reason the concept of the LOLP (loss of load probability) was introduced as discussed in chapter 6. It has been found that to decrease the LOLP from 1% to 0.1%, takes either a huge battery bank capacity or an exceptionally large step-up in size for one of the renewable energy systems. Because of this, where a very high degree of reliability of supply is required, often a standby generator is installed for use when the renewable energy source supplies energy at a rate short of the demand.

The LOLP of a given system can be estimated with knowledge of the variability of the renewable energy resource or resources. The variability of solar radiation, as discussed in chapter 7, can be estimated from the average clearness index for the particular month. The photovoltaic design tables produced using the author's computer model (presented in Appendix E) are all for a 1% LOLP. Because of renewable energy's variability, combinations of renewable energy forms often prove more economic than sole reliance on one type. This is because, based on the law of probability, an extended period of (say) low sunshine is unlikely to coincide with an extended period of low wind power.

9.3 Wind-Photovoltaic Hybrid

Solar radiation levels are characteristically much higher in the summer months, particularly for mid-latitude regions. In contrast, most locations in the world tend to experience maximum average wind velocities over winter (Watson, 1987). Wind and solar radiation are therefore often complementary in terms of their annual distribution.

In New Zealand, wind velocities are higher during the winter period for elevated areas (Cherry, 1987) and so there is a definite complementarity between wind and solar power in this situation. The degree of this complementarity is, however, influenced by the tilt angle chosen for the array. Complementarity diminishes at lower latitudes because of the reduced seasonal fluctuation of radiation levels. Coastal lowland areas along the east coast of New Zealand and inland areas experience the lowest average wind speeds during winter (Cherry, 1987) and so in these situations the advantage of utilising a hybrid of wind-solar power is reduced. Generally, however, the PV-Wind hybrid combination is particularly suited to New Zealand conditions (Ministry of Energy, 1986).

Figure 9.1 is based on a real example using a typical mountain top communications site in the northern hemisphere. As can be seen from the graph, the stand alone wind turbine system can provide the necessary power for most of the year. The deficit in the summer months is met by a small Photovoltaic array. This method of meeting the demand was calculated as being more cost effective than using a large battery bank or a larger wind turbine (Mayer, 1985), even based on 1985 array prices.

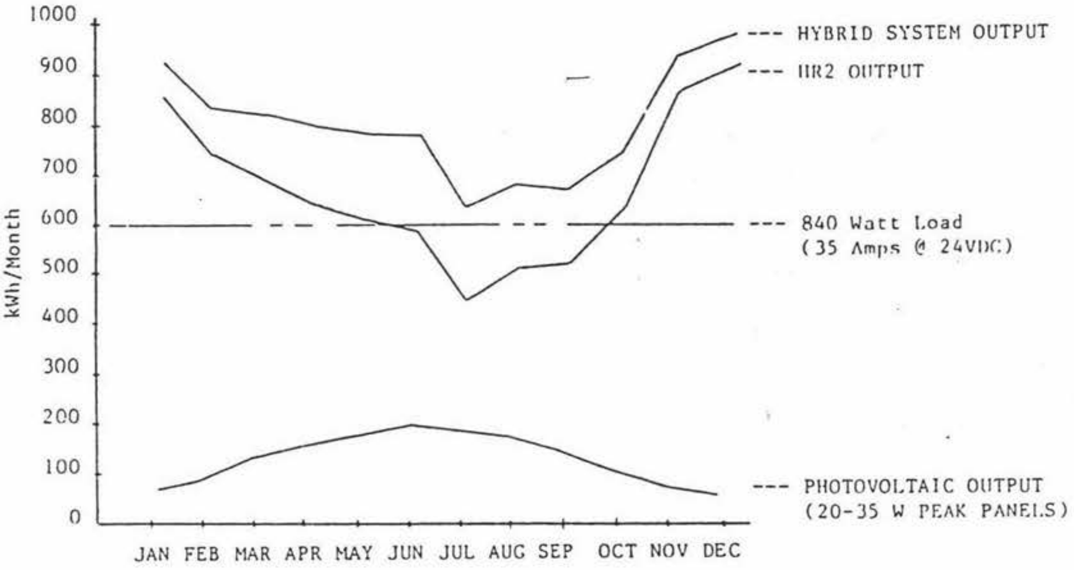

Figure 9.1 Turbine Output showing Photovoltaic Contribution (Mayer, 1985)

9.4 Diesel Generators

Stand alone diesel generators are commonly found in remote area power system applications where more than two to three kilowatt hours of electricity are used per day (Ministry of Energy, 1986). A diesel generator operates more efficiently, more reliably and requires less maintenance when it operates at full load (Dure, 1985).

9.4.1 Disadvantages of Diesel Generators

The main disadvantage of using solely diesel generators is that power is only available when the generator is running, and that often it needs to be turned on and off very frequently (normally a minimum loading of 30% is suggested to avoid bore glazing and oiling up of the silencer (Lipman, 1988).

Diesels are not only expensive but they are often noisy as well. There are some methods available to reduce the noise levels[12]. The most effective, however, is to minimise the time for which the generator operates.

9.4.2 Fuel Efficiency

The fuel efficiency of diesel sets is related to the load placed on them as well as their age. They operate most efficiently at full load. It is a relatively simple matter to install a watt-hour meter in the supply circuit to determine the amount of electricity being consumed over a given time. By recording fuel consumption over the same period one is able to derive a kWh per litre figure. The efficiency with which diesel is converted into electricity is, however, very dependent on the loading. Figure 9.2 shows the efficiency with which fuel is burnt as a function of loading.

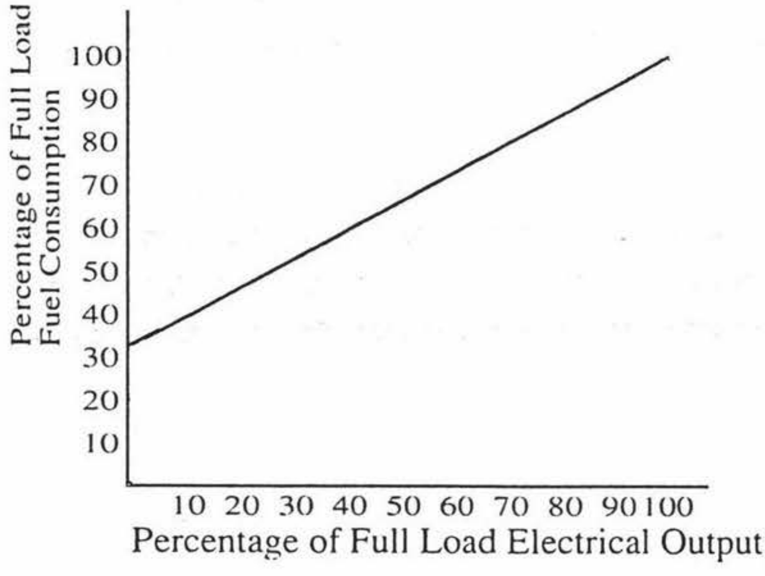

Figure 9.2 Fuel Usage versus Electrical Load (Adapted from Lipman, 1988).

[12]These include physical barriers, increasing the distance, lining the generator shed with material which absorbs sound, using exhaust silencers, and locating the exhaust on the far side of the shed.

9.4.3 Diesel Generator plus Batteries

A diesel generator can be used to charge deep cycle batteries. An inverter is then used to convert the battery DC to AC in order to run appliances. In many cases the cost of electricity produced by a diesel-battery system is 40% less than that produced by a diesel generator alone (Lipman, 1988). Such systems tend to operate as 'cyclic charging systems' where the diesel is run at full output (and therefore maximum efficiency) until the battery bank is recharged and then turned off. Operating the generator in this manner minimises diesel engine coking and maintenance costs.

It has only been since inverters have been available, which have a reasonably high efficiency for all loading conditions, have such systems been viable. Care must be taken to carefully match the generator to the battery bank so that when charging, the generator is optimally loaded (Ministry of Energy, 1986).

9.4.4 Sizing the Battery Bank Associated with a Diesel-Hybrid System

Batteries are often used in combination with diesel generators to reduce the number of start and stop cycles. Shorter term energy storage is often in the form of flywheels or hydraulic systems (Watson, 1987).

The battery bank should be able to accept the full charge of the diesel generator over the optimum run time for the generator, often about 8 hours (Mayer, 1985). In addition to this it needs to be able to accept the full output of the renewable energy source/s. The battery bank should ideally not be required to discharge at a rate greater than 10% of its total capacity (Ministry of Energy, 1986).

9.5 Wind-Diesel Systems

Where a good wind site is available, combining a wind generator with a diesel generator can significantly reduce the cost of power. With larger systems, say over 10 kW, a diesel generator often remains the primary energy producer although it may often be linked to a wind turbine to reduce the generator's running costs

A wind-diesel system has advantages over sole reliance on diesel. Part load diesel operation is extremely inefficient and expensive. The addition of a small wind system can provide the off peak load requirement while leaving the diesel set for main loads (Watson et al, 1983).

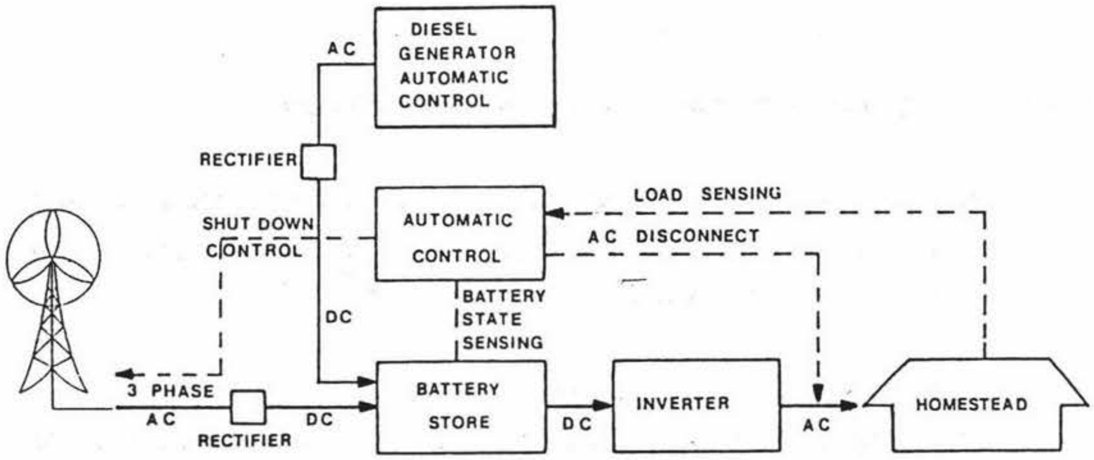

Figure 9.3 Hybrid Wind-Diesel Electric Power System (Edwards, 1986 - adapted from Langworthy, 1984).

9.5.1 Types of Generators on the Wind Turbine used in a Wind-Diesel Hybrid

The difficulty with the induction generator is that it requires an external source of reactive power. The synchronous generator is self energising but may experience stability problems. In practice induction generators are used in conjunction with a continuously spinning synchronous generator on the AC line to provide reactive power (Lipman, 1988).

9.6 Hybrid System Controllers

The use of micro-processors now allows a much greater degree of control over the system. One of the main uses of controllers is to protect the batteries from being either over or undercharged and so maximise the life of the battery bank (Todd, 1987). Use is made of regulators and controllers which can monitor temperature, sense load, degree of battery charge and switch in extra load when the battery is fully charged. The controller also controls the diesel generator, if there is one. It starts the generator and introduces an extra load, if required, to bring it up to its peak operating output (Watson, 1982).

The controller may also be required to perform the following additional tasks: Battery cell equalisation; rectification of input; blocking reverse input current flow; limiting system load voltage, informing the user of system status; and improving matching between source and the load or battery in order to optimise power transfer (Todd, 1987).

9.7 Sizing the Battery Bank Associated with Two Renewable Energies

Hybrid systems tend to require less energy storage capacity compared to where there is reliance on only one form of energy. The amount of storage required when a hybrid system, say of wind and solar, is used will depend on the following:

1. the proportion of the demand met by each energy form,
2. the period for which the wind-solar radiation falls to a point where it can no longer be utilised,
3. the loss of load probability (LOLP).

The amount of storage capacity required when two renewable energy forms operate together can be estimated by the following procedure:

9.8 Battery Sizing Procedure

Step 1: The storage capacity requirement based on reliance on the primary energy source alone is determined.

Step 2: The amount of energy likely to be contributed by the other energy forms during this period, based on daily averages, is calculated.

Step 3: The result of the above is multiplied by 1 / battery storage efficiency, typically 85%.

Step 4: The amount of storage capacity required for the hybrid system is then the value derived from step 1 less the value determined in step 3.

The LOLP of a hybrid system with given size components will always be decreased by increasing the battery bank capacity.

9.9 Sizing Hybrid Systems

The components of a hybrid system must be sized correctly to ensure the right amount of energy is delivered on an annual or monthly basis to meet the energy demand. The optimum size of the various components is largely influenced by their respective costs in relation to their energy contribution. To make accurate cost assessments these should be discounted over the expected life of the particular component.

The magnitude of the various renewable energy resources has a major influence on the most appropriate size combination in any hybrid system. This factor, in combination with a price analysis, can be used to determine which renewable energy source (if any) is the cheapest and therefore most appropriate primary energy source (assuming a given LOLP and others factors being equal) and which the secondary.

9.9.1 Procedure for Sizing Hybrid Systems

Step 1: The demand, and its variability on a monthly and preferably daily basis, is specified.

Step 2: The size of the system required, utilising the most promising single energy source to meet the power demand calculated in step 1 (chapter 6 for solar power, chapter 7 for wind power, and chapter 8 for micro-hydro), is calculated.

Step 3: Such a system is priced on the market, the cost annualised (chapter 10), and divided by the energy demand to obtain a $/kWh figure. One should include associated running and maintenance costs to obtain an accurate figure.

Step 4: The amount of battery storage required is determined. This is then priced and annualised. As for the above (dividing by the energy demand rather than the storage capacity), a cost per kWh for the battery storage capacity is calculated.

The figure calculated in step 3 is then added to the figure calculated in step 4 to obtain the total cost of meeting the demand by the sole energy source (this figure will be referred back to as a bench mark).

Step 5[13]: The next most favourable energy form or a diesel generator is selected. The proportion of the total energy demand to be met by this energy form is then arbitrarily allocated.

Step 6: Step 3 is repeated for the original energy form for the reduced amount of the energy produced. Step 3 is repeated again for the second energy form to derive a $/kWh figure for both energy forms. These two figures, each containing a cost for generation and a cost for storage, are added together.

The reduced battery capacity requirement is then calculated as shown in section 9.8. A new cost per kWh of battery storage is then calculated.

Step 7: A cost for the extra control and regulation equipment required for the hybrid system is determined and again this is expressed as a cost per kWh figure. Adding this figure to those derived from step 6 results in the total cost of meeting the demand with this particular combination.

Step 8: The components of energy to be contributed by each energy form are altered and step 5 and 6 repeated until the final $/kWh result is at a minimum. These proportions are the most economic.

9.9.2 Hybrid Sizing Example

Based on the following assumptions:

A steady demand of 6 kWh per day
4 days storage required
5% Discount rate used
Photovoltaic array cost of NZ$13 per peak watt
Cost of stand alone turbine = $14,000
Cost of turbine used in hybrid system = $8,500
$200 per year maintenance spent on both stand alone and hybrid systems
Additional control system cost in hybrid system of $1,500
Turbine life of 20 years

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[13] For high penetration of wind power the wind turbine rating may typically be about twice the diesel rating (Lipman, 1988).

Photovoltaic array life of 15 years

Array output kept constant during the year by altering tilt angle

Battery life of 10 years

Maximum depth of battery discharge = 50%

Overall battery efficiency of 85%

Life of control equipment of 20 years

Step 1: 6 kWh per day demand

Step 2: Using solely wind power the following turbine is selected:

Cut-in wind speed: 4 m/s
Rated wind velocity: 12 m/s
Furling wind velocity: 20 m/s

Rated output: 1.5 kW

According to table G11 in Appendix G, the amount of power produced by the above turbine where there is an average wind speed of 5 m/s is 3,060 kWh per year.

Step 3: The cost of the turbine is $14,000. Associated annual maintenance and running costs come to $200

Using table 10.2, the discount factor which applies, for a life of 20 years and a discount rate of 5%, is 12.5.

$14,000/12.5 = $1,120

Annualised cost is 1,120 + 200 = $1,320

$1,320/2,190 kWh = 60c per kWh for the wind turbine alone

(amount of useful energy equals the daily demand times 365, ie. is 6 x 365 = 2,190 kWh)

Step 4: Storage required = 56.5 kWh

Obtained by: 4 x 6 kWh x 1/.5 x 1/.85 = 56.5 kWh where 0.5 is the depth of discharge and 0.85 is the battery efficiency. Based on a battery cost of $500 per kWh

56.5 x $500 = $28,250

From table 10.2 the factor which applies for a discount rate of 5% and a life of 10 years is 7.72.

28,250/7.72 = $3,659

$3,659/2,190 kWh = $1.67

The total cost of meeting the demand with this particular turbine and battery combination = 0.60 + 1.67 = $2.27/kWh.

Step 5: Hybrid System
About 60% wind power and 40% photovoltaic power.

Step 6: Calculating energy and cost for both energy forms

Wind Turbine

Cut-in wind speed: 3 m/s
Rated wind velocity: 11 m/s
Furling wind velocity: 15 m/s
Rated output: 0.5 kW

From table G5 in Appendix G, where there is an average wind speed of 5 m/s, the turbine produces 1,420 kWh per year (average of 3.9 kWh per day), while only 3.5 kWh is needed on an average day - based on the proportions estimated above.

Assumed cost of turbine is $8,500.
The discount factor which applies is still 12.5.

Annualised cost = 8,500/12.5 = $680
Plus annual $200 maintenance = $880

Amount of useful energy produced is 3.5 kWh x 365 = 1278 kWh per year.

$880/1278 kWh = $0.69/kWh for turbine contribution.

Photovoltaic Cells

Assume $6,500 was spent on photovoltaic cells @ $13 per peak watt (500 Wp rated system).

Assuming average radiation conditions of 5 kWh per day per m^2 during the summer months when the wind is the lowest.
500 Wp would therefore deliver 5 x 500 = 2.5 kWh per day.

To discount the $6,500 at a rate of 5% over 15 years it needs to be divided by 10.4 (table 10.2)

$6,500/10.4 = $625

Assuming the array output is kept constant at an average of 2.5 kWh per day, the useful output is therefore 2.5 x 365 = 913 kWh.

$625/913 kWh = $0.68/kWh

Revised Storage Requirement

The original storage period required when there was sole reliance on wind power was 4 days. 2.5 kWh per day x 4 days = 10 kWh per day likely to be contributed by the photovoltaic array during this period.

This equates to:

10 x 1/0.5 (DOD) x 1/0.85 (battery efficiency) = 23.5 kWh battery storage capacity

Therefore with the hybrid system only 33 kWh (56.5 - 23.5) is required.

33 x $500 = $16,500
16,500/7.72 = $2,137

$2,137/2,190 kWh = $0.98/kWh

Step 7: Cost of Control Equipment

Assume a cost for control equipment, above what would be incurred by wind turbine, of $1500.

1,500/12.5 = $120

Useful energy still 6 x 365 = 2,190 kWh.

$120/2,190 kWh = $0.055/kWh

Therefore a total cost of supplying power with the wind-photovoltaic hybrid will be:

{0.69 (3.5/6)} + {0.68 (2.5/6)} + 0.98 + 0.055
= 0.40 + 0.28 + 0.98 + 0.055 = $1.72/kWh

A saving over the sole use of a wind turbine of

$2.27 - $1.72 = $0.54 per kWh

This example illustrates how the cost of a hybrid system may be determined. In order to derive the optimum size combination of the various elements of a hybrid system, this procedure would need to be undergone several times in a process of iteration to derive the least cost option, while maintaining an acceptable degree of reliability. This could be relatively easily done using a spreadsheet.

CHAPTER 10

PROJECT EVALUATION AND FINANCIAL COMPARISON

10.1 Financial Assessment

A financial assessment (as opposed to a purely economic one) seeks to look at the financial viability of a project from an individual perspective, and so uses costs adjusted by taxes, subsidies, and interest repayments etc (Derrick et al, 1990).

To make a valid financial comparison between different energy forms, the expected lifetimes, capital costs, running costs and/or maintenance costs must all be taken into account. The most common and recommended method of such a financial assessment is life cycle costing (Lancashire et al, 1987). Such an assessment tends to ignore wider scale concerns such as environmental issues and neither does it consider other factors such as system reliability.

10.2 Life Cycle Costing

This process enables valid comparisons to be made with different energy sources. All future financial costs and benefits are taken into account by discounting them to present day values and then summing them. The resultant value is termed the present worth (present value) of the system.

The present worth can be calculated from equation 10.1.

$$\sum N_{n=1} ([cost\ in\ year\ n] / [1+i]/100]^{m}) \qquad \mathbf{(10.1)}$$

where:
i = discount rate
N = expected system life
n = age of system
m = number of years from the present to year n.

Typically the system life of batteries is taken as 7 years, PV arrays 15 years, wind turbines 20 years, diesel generators and inverters 10 years (Edwards, 1986). The discount rate reflects the opportunity cost of capital where a high rate reflects a relatively low value being placed on future costs and benefits. The adopted treasury discount rate in the UK is normally 5% (Infield & Lipman, 1983). If inflation was 0% then one could simply use the current interest rate figures on deposits. In practice it is tedious to use this formula each time so two tables have been developed by this author using a spreadsheet programme (Quattro Pro). Table 10.1 is for where there is a one off cost or payment at some time in the future.

Example: To find the present worth of a payment of $900 in 8 years time, at a discount rate of 6%, the discount factor is 0.63.

Present Worth = $900 x 0.63 = $567

Table 10.1 should also be used to determine the AC/BC cost ratio for use with the array and battery sizing charts discussed in chapter 6.

Where a cost is to be incurred or a payment made every year over the life of the equipment, to calculate the present worth, Table 10.2 can be used to avoid the tedium of performing the above calculation for every year.

Example: If the annual maintenance cost of a wind turbine is $200 and the expected life is for 20 years, at a discount rate of 14%, the discount factor is 6.62 from table 10.2.

Present Worth = $200 x 6.62 = $1,324

10.2.1 Determining the Annualised Cost

Once the present worth of a system has been determined, the annualised cost can then be calculated. This is the total present worth[14] of the system expressed as an average yearly cost in current dollars, averaged over the expected life of the system. This is done in the reverse manner to discounting by dividing the sum of all of the present worth figures by the appropriate factor from table 10.2.

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[14] Also called the life-cycle cost.

Example: To find the annualised cost of a system with an expected life of 15 years where the sum of the present values is $12,000, and where the discount factor is 6%, the discount factor is 9.71 (Table 10.2).

$12,000 / 9.71 = $1,236 per year

To make comparison easier between systems producing different amounts of power it is helpful to express the result in a cost per unit power produced (or water pumped). To do this the annualised cost is simply divided by the annual total of electricity generated (or water pumped) in one year.

10.3 Example of a Financial Assessment

The following example shows the procedure to determine the true cost of a wind electric system on a $ per Kwh basis.

The data on which this analysis is based is given below:

10 Kw Wind turbine	$33,500
Controller	$6,500
30 m tower	$14,500
Annual Maintenance	$600
Major overhaul @10 years	$3,500
Expected lifetime	20 years
Cut-in Velocity	3 m/s
Rated Velocity	11 m/s
Furling Velocity	20 m/s
Average wind velocity	7 m/s
Inflation Rate	4%
Interest Rate	10%

Step 1: The life cycle costs of the system is determined

Discount rate = Interest - Inflation = 10 - 4 = 6%.

Capital costs = $33,500 + $6,500 + $14,500 = $54,500

Maintenance costs recur annually so using table 10.2, based on a discount rate of 6% and lifetime of 20 years, the discount factor which applies is 11.5.

$600 x 11.5 = $6,900

The major overhaul is a one-off cost so table 10.1 needs to be used based on a discount rate of 6% and 10 years. The discount factor which applies is 0.56.

$3,500 x 0.56 = $1,960

The total life cycle cost is the sum of all of these components:

Total life cycle cost = $54,500 + $6,900 + $1,960 = $63,360

Step 2: The cost is annualised over the life of the system

For a discount rate of 6%, and a life of 20 years the appropriate factor from table 10.2 is 11.5. This time the dollar value is divided by this factor.

$63,360/11.5 = $5,510 per year for the life of the system

Step 3: The unit power cost is calculated

The annual amount of power produced, from table G6 in Appendix G, is 45,220 kWh.

$5,510/45,220 = $0.12/kWh

Therefore the true cost of producing power using the turbine with the characteristics described above is 12 cents per kWh.

Table 10.1 Discount Factors for "One-Off" Costs for Various Discount Rates and Number of Years

Lifetime	Discount Rate (%)					Discount Rate (%)						
(yrs)	2	3	4	5	6	8	10	12	14	16	18	20
1	0.98	0.97	0.96	0.95	0.94	0.93	0.91	0.89	0.88	0.86	0.85	0.83
2	0.96	0.94	0.92	0.91	0.89	0.86	0.83	0.80	0.77	0.74	0.72	0.69
3	0.94	0.92	0.89	0.86	0.84	0.79	0.75	0.71	0.67	0.64	0.61	0.58
4	0.92	0.89	0.85	0.82	0.79	0.74	0.68	0.64	0.59	0.55	0.52	0.48
5	0.91	0.86	0.82	0.78	0.75	0.68	0.62	0.57	0.52	0.48	0.44	0.40
6	0.89	0.84	0.79	0.75	0.70	0.63	0.56	0.51	0.46	0.41	0.37	0.33
7	0.87	0.81	0.76	0.71	0.67	0.58	0.51	0.45	0.40	0.35	0.31	0.28
8	0.85	0.79	0.73	0.68	0.63	0.54	0.47	0.40	0.35	0.31	0.27	0.23
9	0.84	0.77	0.70	0.64	0.59	0.50	0.42	0.36	0.31	0.26	0.23	0.19
10	0.82	0.74	0.68	0.61	0.56	0.46	0.39	0.32	0.27	0.23	0.19	0.16
11	0.80	0.72	0.65	0.58	0.53	0.43	0.35	0.29	0.24	0.20	0.16	0.13
12	0.79	0.70	0.62	0.56	0.50	0.40	0.32	0.26	0.21	0.17	0.14	0.11
13	0.77	0.68	0.60	0.53	0.47	0.37	0.29	0.23	0.18	0.15	0.12	0.09
14	0.76	0.66	0.58	0.51	0.44	0.34	0.26	0.20	0.16	0.13	0.10	0.08
15	0.74	0.64	0.56	0.48	0.42	0.32	0.24	0.18	0.14	0.11	0.08	0.06
16	0.73	0.62	0.53	0.46	0.39	0.29	0.22	0.16	0.12	0.09	0.07	0.05
17	0.71	0.61	0.51	0.44	0.37	0.27	0.20	0.15	0.11	0.08	0.06	0.05
18	0.70	0.59	0.49	0.42	0.35	0.25	0.18	0.13	0.09	0.07	0.05	0.04
19	0.69	0.57	0.47	0.40	0.33	0.23	0.16	0.12	0.08	0.06	0.04	0.03
20	0.67	0.55	0.46	0.38	0.31	0.21	0.15	0.10	0.07	0.05	0.04	0.03
21	0.66	0.54	0.44	0.36	0.29	0.20	0.14	0.09	0.06	0.04	0.03	0.02
22	0.65	0.52	0.42	0.34	0.28	0.18	0.12	0.08	0.06	0.04	0.03	0.02
23	0.63	0.51	0.41	0.33	0.26	0.17	0.11	0.07	0.05	0.03	0.02	0.02
24	0.62	0.49	0.39	0.31	0.25	0.16	0.10	0.07	0.04	0.03	0.02	0.01
25	0.61	0.48	0.38	0.30	0.23	0.15	0.09	0.06	0.04	0.02	0.02	0.01

Table 10.2 Discount Factors for Recurrent Costs Over a Number of Years, for Various Discount Rates

Lifetime	Discount Rate (%)					Discount Rate (%)					
(yr	2	3	4	5	6	8	10	12	14	16	18	20
1	0.98	0.97	0.96	0.95	0.94	0.93	0.91	0.89	0.88	0.86	0.85	0.83
2	1.94	1.91	1.89	1.86	1.83	1.78	1.74	1.69	1.65	1.61	1.57	1.53
3	2.88	2.83	2.78	2.72	2.67	2.58	2.49	2.40	2.32	2.25	2.17	2.11
4	3.81	3.72	3.63	3.55	3.47	3.31	3.17	3.04	2.91	2.80	2.69	2.59
5	4.71	4.58	4.45	4.33	4.21	3.99	3.79	3.60	3.43	3.27	3.13	2.99
6	5.60	5.42	5.24	5.08	4.92	4.62	4.36	4.11	3.89	3.68	3.50	3.33
7	6.47	6.23	6.00	5.79	5.58	5.21	4.87	4.56	4.29	4.04	3.81	3.60
8	7.33	7.02	6.73	6.46	6.21	5.75	5.33	4.97	4.64	4.34	4.08	3.84
9	8.16	7.79	7.44	7.11	6.80	6.25	5.76	5.33	4.95	4.61	4.30	4.03
10	8.98	8.53	8.11	7.72	7.36	6.71	6.14	5.65	5.22	4.83	4.49	4.19
11	9.79	9.25	8.76	8.31	7.89	7.14	6.50	5.94	5.45	5.03	4.66	4.33
12	10.6	9.95	9.39	8.86	8.38	7.54	6.81	6.19	5.66	5.20	4.79	4.44
13	11.3	10.6	9.99	9.39	8.85	7.90	7.10	6.42	5.84	5.34	4.91	4.53
14	12.1	11.3	10.6	9.90	9.29	8.24	7.37	6.63	6.00	5.47	5.01	4.61
15	12.8	11.9	11.1	10.4	9.71	8.56	7.61	6.81	6.14	5.58	5.09	4.68
16	13.6	12.6	11.7	10.8	10.1	8.85	7.82	6.97	6.27	5.67	5.16	4.73
17	14.3	13.2	12.2	11.3	10.5	9.12	8.02	7.12	6.37	5.75	5.22	4.77
18	15.0	13.8	12.7	11.7	10.8	9.37	8.20	7.25	6.47	5.82	5.27	4.81
19	15.7	14.3	13.1	12.1	11.2	9.60	8.36	7.37	6.55	5.88	5.32	4.84
20	16.4	14.9	13.6	12.5	11.5	9.82	8.51	7.47	6.62	5.93	5.35	4.87
21	17.0	15.4	14.0	12.8	11.8	10.0	8.65	7.56	6.69	5.97	5.38	4.89
22	17.7	15.9	14.5	13.2	12.0	10.2	8.77	7.64	6.74	6.01	5.41	4.91
23	18.3	16.4	14.9	13.5	12.3	10.4	8.88	7.72	6.79	6.04	5.43	4.92
24	18.9	16.9	15.2	13.8	12.6	10.5	8.98	7.78	6.84	6.07	5.45	4.94
25	19.5	17.4	15.6	14.1	12.8	10.7	9.08	7.84	6.87	6.10	5.47	4.95

CHAPTER 11

SUMMARY AND DISCUSSION

After the introduction to the topic in chapter 1, the review of the literature was presented in chapter 2. Electricity theory, power transmission and energy storage, as they relate to renewable energies, was examined in chapter 4 to provide a framework on which to build. Chapter 5 then considered the important area of assessing the demand of either electricity or water over a specified time interval. This is often a weak link in the design process and so was given considerable attention. Without an accurate demand assessment the resulting design may be considerably over or undersized.

Chapters 6 through to 8 then examined the three energy forms under consideration, presenting key design information. They also provided an introduction to the use of the associated design charts generated using the computer models created.

The design charts associated with the photovoltaic chapter included charts to:

1. convert sunshine hours to radiation received on a horizontal surface based on the month and the latitude;

2. convert radiation received on a horizontal surface to that received on a specified tilt based on latitude and tilt angle;

3. enable a selection to be made of the most cost effective combination of battery and array size for a given load based on array cost, battery cost, standard deviation of the insolation, maximum depth of discharge permitted, and radiation.

Regional coefficients were derived by the author for the areas in New Zealand for which sunshine hour data exists. These coefficients can be used to improve the accuracy with which sun hour data can be used to determine radiation levels in nearby areas to within less than 10% of the true radiation levels. The information in the photovoltaic chapter can be used to determine the size of the photovoltaic array required, and battery storage (if any) required for a given application.

The design charts associated with the wind chapter enables the output of a turbine with specified characteristics of cut-in velocity, rated velocity and furling (cut-out) velocity to be determined. Nomograms are provided in the wind chapter which enable wind pump rotors to be sized, based on water volume, head and average wind speed. These design charts and nomograms would enable someone to determine the optimum wind turbine parameters for a particular situation.

Chapter 9 examined the issue of hybrid systems where two or more forms of energy supply are used in combination. The information presented here is not sufficient to enable the design of a hybrid system but presented the important design considerations.

Chapter 10 is presents a useful methodology for the financial evaluation of renewable energy systems with different lifetimes and operating costs in order to provide a financial criteria for system selection. Without such an analysis the most economically attractive option is too often overlooked, simply because the financial advantages associated with it are not immediately obvious.

This thesis provides a very good summary of the application of renewable energy forms. The way in which it is presented, and the information it contains, enables an individual to make a preliminary estimate of the preferred energy type, and to obtain an approximate cost of generating power with a particular method. This information is valuable as equipment suppliers are often keen to push their particular energy system, regardless of whether it is the most appropriate or not.

The validation section of the photovoltaic and the wind chapters showed that the results presented in the various design charts are consistent with existing data, and therefore the computer models generated by the author are reliable.

The micro-hydro chapter enables the optimum type and size turbine to be selected for any given application. It discusses associated aspects such as penstocks and governing etc.

This study presents and discusses most of the important design considerations for each energy form. The information contained in this thesis will, in many cases, be sufficient to determine the parameters of a renewable energy system. Professional assistance should still generally be sought to confirm a design.

11.1 Suggestions for Further Research

An important area, and one which will undoubtedly experience a lot of growth, is that of hybrid power generation. Currently it is still difficult to size the components of a hybrid system optimally. The relative sizes of hybrid components are largely influenced by prices and so ideally this would be built into the analysis, perhaps with the use of cost ratios such as employed in section 6.15.4 for photovoltaic array and battery sizing.

The linking of diesel generators to a renewable energy source or sources demands an excellent control system. More work also needs to be done in this area.

Renewable energies will, without a doubt, become increasingly utilised as the world discovers the economic and environmental benefits they offer. It is the author's desire, that in the production of this thesis, he has in some small way contributed towards this process.

GLOSSARY

ELECTRICITY

AC	Alternating electric current
Alternator	A generator which generates AC power
Amp-hour	A unit of battery capacity calculated by multiplying current flow in amps by the number of hour it flows
Asynchronous Generator	A generator designed to feed AC power into an existing power system. The generator rotation is not synchronised with the mains frequency, so fixed speed operation is not required (refer to induction generator)
DC	Direct electric current. Unlike AC current flows in one direction only
Diode	An electric device which allows electric current to flow in one direction only, used as a rectifier
Dummy Load	An electrical load, usually a heating element, used to dissipate excess energy
Frequency	The number of oscillations (cycles) per second expressed in hertz (Hz)
Generator	Converts mechanical shaft power into electrical power, AC or DC
Inverter	Converts DC to AC (refer to synchronous inverter)
Kilowatt (kW)	Unit of power where one watt equals one joule per second
Kilowatt-Hour(kWh)	Unit of electrical energy (1,000 watt hours)
kVa	1,000 volt-amperes. Used to describe power from an alternator with a power factor less than one
Peak Load	The peak power requirement when several appliances are operated simultaneously
Power Conditioning	Modification of the power supply to meet the user needs in terms of type of current and voltage

Rectifier	Converts AC to DC (refer to diode)
Resistor	A device which is used to limit current. Resistance measured in ohms
Sine Wave	Continuous period oscillation used to represent AC voltage and current waveforms generated by rotary inverters and alternators
Synchronous Inverter	Inverts DC to AC using another AC source. AC output is synchronous with outside AC source
Synchronous Generator	AC generator which operates which operates together, and is synchronised with, another AC power source. It rotates at a constant speed
Voltage Regulator	Regulates the voltage of the power supply system varying the amount of current
Voltage (V)	Electromotive force which causes the current flow
Watt (W)	Unit of electric power. The power required to do work at the rate of one joule per second
Watt-Hour (Wh)	Unit of electrical energy

BATTERY

Battery Efficiency	The ratio of ampere-hours removed from a battery during a discharge to the ampere-hours required to restore the initial capacity
Electrolyte	The medium which provides the ion transport mechanism between the positive and negative electrodes of a cell
Capacity	The total number of kilowatt hours that can be withdrawn from a fully charged cell or battery
Charge Rate	The current applied to a battery to restore its available capacity
Cut-off Voltage	The battery voltage at which discharge is terminated. This is generally a function of discharge rate. Discharge beyond the specified cut-off voltage may permanently damage the battery

Cycle Life	The number of cycles, to a specified depth, that a battery can undergo before failing to meet its specified capacity
Deep Discharge Cycle	One discharge-charge sequence to a specified depth of discharge. The withdrawal of a significant percentage of rated capacity (50% or more)
Depth of Discharge	The ampere-hours removed from a fully charged battery expressed as a function of rated capacity
Discharge Rate	The current removed from a battery
Equalisation	The process of restoring all cells in a battery to an equal state of charge
Hours of Capacity	The total number of hours for which a fully charged battery is capable of supplying the system load before reaching the maximum depth of discharge
Rated Capacity	The manufacturer's estimate of the total number of ampere hours that can be withdrawn from a new cell or battery for a specified discharge rate, temperature and cut-off voltage
Self Discharge	The process by which the available capacity of a cell is reduced by internal chemical reactions

PHOTOVOLTAIC

Angle of Incidence	The angle between the direction of the sun and the perpendicular to the surface on which the sunlight is falling
Azimuth Angle	The angle between the south-north line at a given location and the projection of the earth-sun line in the horizontal plane
Declination	The angular position of the sun north (+) or south (-) of the plane of the earth's equator. It is a function of the time of the year
Diffuse Insolation	The sunlight scattered by atmospheric particles that arrives at a direction other than the direction of direct sunlight
Extraterrestrial Radiation	The radiation received at the outer limit of the earth's atmosphere

Global Solar Radiation	The sum of the direct and diffuse solar radiation incident on a given plane
Insolation	An imprecise term often meaning solar irradiance or sunlight penetration
Irradiation	The radiant energy falling per unit area on a plane per unit time
Latitude	The angular distance north (+) or south (-) of the equator, measured in degrees
Load Factor	The ratio of the average output of an energy system to the rated output
Local Solar Time	A system of astronomical time in which the sun always crosses the true north-south meridian at 1200 hours
Orientation Angle	The direction that an array faces expressed as the azimuth angle of the horizontal projection of the surface normal
Photovoltaic Effect	The generation of a voltage when radiant energy falls on the boundary between certain dissimilar substances in close contact
Photovoltaic Cell	A semiconducting device that converts sunlight into electrical power. The conversion process is called the photovoltaic effect
Pyranometer	An instrument for measuring the global (diffuse plus direct) solar radiation on a plane
Pyrheliometer	An instrument using a collimated detector for measuring direct radiation
Reflectivity	The ratio of light reflected from a surface to the light falling on that surface
Scattering	The interaction of radiation with matter where its direction is changed
Solar Constant	The intensity of solar radiation beyond the earth's atmosphere, at the average earth-sun distance, at a surface perpendicular to the sun's rays
Solar Cell	Photovoltaic cell
Solar Radiation	The radiant energy received from the sun directly as a beam radiation and diffusely as atmospherically scattered and ground reflected radiation
Solar Azimuth	The projected angle between a straight line from the position of the sun to the point of observation and due north

Solar Noon For any given location the solar noon is the local time of day when the sun is at its highest altitude for that day

Solar Declination The angle subtended between the earth-sun line and the plane of the equator, where north is positive

Sunset Hour Angle The hour angle occurring at sunset

Tracking Collector A collector that can rotate about one or two axes to face the sun

Zenith The highest point of the sky hemisphere, the point vertically above the observer

WIND

Aero-generator Electric power generating wind turbine

Capacity Factor The ratio of the average power delivered by the system to its maximum rating. It describes the relationship between the net amount of energy delivered to the load and the potential amount of energy which the generating system is capable of delivering

Cut-in Wind Speed Wind velocity at which turbine first starts producing useful power

Cut-out Wind Speed Furling, shut down speed

Demand Profile Graph of the daily power demand

Drag The force on an airfoil or wind turbine blade which acts in the same direction as the wind flow

Efficiency Power output of a device divided by the power input to that device (refer to power coefficient)

Energy The measure of the amount of work usually expressed in kilowatt-hours (kWh). Energy is power multiplied by time

Energy Density Energy per unit weight or volume

Furling Speed	Wind velocity at which the turbine stops functioning to protect it from damage
Lift	The force on a turbine blade which acts at right angles to the airflow
Load Factor	The ratio of the average load to the peak load. For the typical off-grid homestead the average load factor is about 5%
Overall Power Coefficient	Ratio of the power output of the wind machine to the available in the wind stream. It includes the electrical and mechanical losses. This is a more exact expression for efficiency
Power Density	Power per unit cross sectional area of the wind stream measured in watts per meter square
Power Factor	Ratio of AC power available to the power calculated from the product of voltage and current. DC generators are have a power factor of one
Power Duration Curve	Based on the same information as the velocity duration curve. The ordinates are simply cubed since power is proportional to the wind speed cubed
Power Coefficient	Ratio of the power extracted by the wind machine to the power available in the wind stream under specified conditions of wind speed and tip speed ratio etc. This varies with the design of the rotor
RAPS	Remote Area Power Supply
Rated Power	Rated turbine power output in W or kW, usually corresponds to its maximum power
Rated Wind Speed	Lowest wind speed at which rated power is produced and is one of the most important considerations in the design of a wind driven generator
Rated Efficiency	Power conversion efficiency at the rated speed of the turbine
Solidity	Ratio of rotor blade surface area to swept area of the entire wind rotor
Specific Output	Energy output of a particular machine for a particular site over a given time period, often a year
Specific Power Density	Power per unit cross sectional area of the wind stream (power and is measured in watts per square metre
Swept Area	Area 'swept' by the turbine rotor as it rotates

Tip Speed Ratio	Ratio of the speed of the tip of the rotor blades to the speed of the wind stream
Velocity Duration Curve	Range of wind speeds and the number of hours which the speed is above or equal to a certain value
V_{match}	Wind speed at which the rotor design characteristics will provide maximum energy for a given wind regime
WECS	Wind energy conversion system
Windmill	Older term for wind turbines. Still used for high solidity machines commonly used for pumping water

FINANCIAL

Capital Cost	The Cost of the System and its associated components paid at the beginning of its life
Recurrent Costs	Any Costs which are ongoing throughout the life of the system, for example, maintenance
Investment Cost	The cost associated with borrowing or lending. Money is worth less in the future than it is today because of both inflation and because money now can be invested.
Discount Rate	The opportunity cost of making an investment. Often regarded as being the interest rate less the inflation rate
Discounting	The reduction in the value of a future payment calculated at a given discount rate to establish its present value
Lifetime	The maximum period during which an investment can be used productively

APPENDICES

Appendix A: Appliance Power Rating and Energy Demand

(Reproduced from Edwards, 1986. Used with the permission of Energy Management, NZ)

Electric Ranges and Cooking

Persons in Household	Estimated kWh per Quarter	Estimated kWh per Day
1	150	1.6
2	220	2.4
3	290	3.2
4	360	4.0
5	430	4.7
6	500	5.5
7	570	6.3
8	640	7.0

These figures are approximately the same regardless of the type of electric range, rangette, stove, stovette, fry-pan, griller or combination of these in use. For more accurate calculations use the following :

Cooking Appliance		Typical Rating (watts)
Crockpot		150
Frying pan		1200
Griller		1200
Vertical griller		1800
Rangette, Stovette		2400
Range, Stove	from	7000
	to	12000
- 16 cm dia hotplate		1250
- 20.5 cm dia hotplate		2100
- 20.5 cm x 25.5 cm grill/boiler		2000
- 19 cm x 38 cm grill/boiler		2400
- 25.5 cm x 30.5 cm grill/boiler		2750
- ovens	from	1800
	to	2500
Wall ovens	from	2500
Domestic Microwave oven		1300 (input)

Kitchen Appliances

	Average Rating (watts)	Estimated kWh per Quarter
Coffee grinder	100	1
Coffee percolator	600	14
Dishwasher	2400	200
Food blender	450	3
Food mixer	110	4
Food warmer	400	10
Garbage disposal	500	4
Immersion heater:		
large	2400	
small	1500	
Jug	1800	75
Juice extractor	300	2
Kettle	1500	75
Toaster (manual)	600	20
(auto)	1500	25
Sandwich maker	600	3
Range hood	80	6

Refrigeration

	Average Rating (watts)	Estimated kWh per Quarter
Refrigerators -		
Conventional	150	80-290
Two-door	250	170-400
Frost free	350	170-600
Freezers -		
Chest type	200	150-260
Vertical	200	230-310
Frost free	250	260-330

Lighting

Lamps - incandescent	40 watts
	60 watts
	100 watts
Lamps - fluorescent	
20 W, 600 mm (2 ft)	30 watts
40 W, 1200 mm (4 ft)	50 watts

Lighting (average home) 175 kWh per quarter

Laundry Appliances

	Average Rating (watts)	Estimated kWh per Quarter
Clothes dryers -		
Cabinet type	2400	500
Rotary plug-in	2400	150
" fixed wiring	4000	135
Iron - automatic	1000	25
- steam	1000	30
Washing machines -		
Washing action	250	14
Heating element	2400	80
Wash boiler with fixed wiring	4000	80

Electric Water Heating

Persons in Home	Litres (gal) per Person per Day	kWh per Day	kWh per Quarter
1	From 45 (10)	3.6	330
	To 75 (17)	6.0	550
2	From 45 (10)	7.3	660
	To 65 (14)	10.4	950
4	From 40 (9)	12.8	1170
	To 55 (12)	17.6	1600
6	From 30 (7)	14.4	1310
	To 45 (10)	21.6	1970
8	From 25 (6)	16.0	1460
	To 40 (9)	25.6	2330

Other Appliances

	Average Rating (watts)	Estimated kWh per Quarter
Aquarium Heater	100	140
Blankets -		
Single: preheating	75	7
all-night use		21
Double: Preheating	120	10
all-night use		32
Clock	2	5
Electric drill	500	5
Fans -		
250 mm (10 in)		
Exhaust or circulating	50	14
400 mm (16 in)		
Circulating	70	7
Floor polisher	250	5
Hair dryer	1000	*
Medical lamp (infra-red heat)	250	*
Electric motors -		
- 1/4 kW	290	
- 1/2 kW	550	
Radio	100	30
Record player	120	*
Sewing machine	75-120	*
Swimming pool Filter	300 - 1000	*
Television set	200	90
Vacuum cleaner	500	13
Video recorder	100	45
Water bed heaters	325	710 (W) 355 (S)

* Varies in use.

Appendix B: Relating Sunshine Duration to Radiation on a Horizontal

Table B1: Global Radiation, H, kWh/m2 per day
based on Month's Daily Average of 3 Sunshine Hours

Latitude

	0	-5	-10	-15	-20	-25	-30	-35	-40	-45	-50	-55	-60
Jan	4.0	4.2	4.3	4.3	4.3	4.2	4.1	3.9	3.6	3.3	2.9	2.4	2.0
Feb	4.2	4.3	4.3	4.3	4.2	4.0	3.8	3.6	3.3	3.0	2.6	2.2	1.8
Marc	4.2	4.2	4.2	4.0	3.9	3.7	3.4	3.1	2.8	2.5	2.1	1.8	1.5
April	4.1	4.0	3.8	3.6	3.4	3.1	2.8	2.5	2.2	1.9	1.6	1.3	1.0
May	3.9	3.7	3.5	3.2	2.9	2.6	2.3	2.0	1.7	1.4	1.1	0.8	0.5
June	3.7	3.5	3.3	3.0	2.7	2.4	2.1	1.7	1.4	1.1	0.8	0.6	0.3
July	3.8	3.6	3.4	3.1	2.8	2.5	2.2	1.8	1.5	1.2	0.9	0.7	0.4
Aug	4.0	3.8	3.7	3.4	3.2	2.9	2.6	2.3	2.0	1.6	1.3	1.1	0.8
Sept	4.1	4.1	4.0	3.9	3.7	3.4	3.2	2.9	2.6	2.2	1.9	1.6	1.3
Oct	4.2	4.2	4.2	4.2	4.0	3.9	3.7	3.4	3.1	2.8	2.4	2.1	1.7
Nov	4.1	4.2	4.3	4.3	4.2	4.1	4.0	3.8	3.5	3.2	2.8	2.4	1.9
Dec	4.0	4.1	4.3	4.3	4.3	4.2	4.1	3.9	3.6	3.3	2.9	2.5	2.0

Table B2: Global Radiation, H, kWh/m2 per day
based on Month's Daily Average of 4 Sunshine Hours

Latitude

	0	-5	-10	-15	-20	-25	-30	-35	-40	-45	-50	-55	-60
Jan	4.5	4.7	4.8	4.9	4.9	4.8	4.7	4.5	4.3	4.0	3.6	3.2	2.7
Feb	4.7	4.8	4.8	4.8	4.7	4.6	4.4	4.2	3.9	3.6	3.3	2.9	2.5
Marc	4.7	4.7	4.7	4.6	4.4	4.2	4.0	3.7	3.4	3.1	2.7	2.3	2.0
April	4.6	4.5	4.3	4.1	3.9	3.6	3.3	3.0	2.7	2.3	2.0	1.6	1.3
May	4.3	4.1	3.9	3.6	3.4	3.0	2.7	2.4	2.0	1.7	1.3	1.0	0.7
June	4.2	4.0	3.7	3.4	3.1	2.8	2.4	2.1	1.7	1.4	1.0	0.7	0.4
July	4.2	4.0	3.8	3.5	3.2	2.9	2.5	2.2	1.8	1.5	1.2	0.9	0.5
Aug	4.5	4.3	4.1	3.9	3.6	3.3	3.0	2.7	2.4	2.0	1.7	1.4	1.0
Sept	4.6	4.6	4.5	4.4	4.2	3.9	3.7	3.4	3.1	2.7	2.4	2.0	1.7
Oct	4.7	4.7	4.7	4.7	4.6	4.5	4.3	4.0	3.7	3.4	3.1	2.7	2.3
Nov	4.5	4.7	4.8	4.8	4.8	4.8	4.6	4.4	4.2	3.9	3.5	3.1	2.6
Dec	4.4	4.6	4.8	4.9	4.9	4.9	4.8	4.6	4.3	4.1	3.7	3.3	2.7

Table B3: Global Radiation, H, kWh/m2 per day
based on Month's Daily Average of 5 Sunshine Hours

Latitude

	0	-5	-10	-15	-20	-25	-30	-35	-40	-45	-50	-55	-60
Jan	4.9	5.1	5.3	5.4	5.4	5.4	5.3	5.2	4.9	4.7	4.3	3.9	3.4
Feb	5.1	5.2	5.3	5.3	5.3	5.2	5.0	4.8	4.6	4.3	3.9	3.5	3.1
Marc	5.2	5.2	5.1	5.0	4.9	4.7	4.5	4.2	3.9	3.6	3.2	2.9	2.5
April	5.0	4.9	4.7	4.5	4.3	4.0	3.7	3.4	3.1	2.7	2.3	2.0	1.6
May	4.8	4.5	4.3	4.0	3.7	3.4	3.1	2.7	2.3	2.0	1.6	1.2	0.8
June	4.6	4.3	4.1	3.8	3.4	3.1	2.7	2.4	2.0	1.6	1.2	0.9	0.5
July	4.6	4.4	4.2	3.9	3.5	3.2	2.9	2.5	2.1	1.8	1.4	1.0	0.6
Aug	4.9	4.7	4.5	4.3	4.0	3.7	3.4	3.1	2.7	2.4	2.0	1.6	1.3
Sept	5.1	5.0	4.9	4.8	4.6	4.4	4.2	3.9	3.6	3.2	2.9	2.5	2.1
Oct	5.1	5.2	5.2	5.2	5.1	5.0	4.8	4.6	4.3	4.0	3.7	3.3	2.9
Nov	5.0	5.1	5.3	5.3	5.3	5.3	5.2	5.0	4.8	4.5	4.2	3.8	3.3
Dec	4.9	5.1	5.3	5.4	5.4	5.4	5.4	5.2	5.0	4.8	4.4	4.0	3.5

Table B4: Global Radiation, H, kWh/m2 per day
based on Month's Daily Average of 6 Sunshine Hours

Latitude

	0	-5	-10	-15	-20	-25	-30	-35	-40	-45	-50	-55	-60
Jan	5.3	5.5	5.7	5.8	5.9	5.9	5.9	5.7	5.6	5.3	5.0	4.6	4.1
Feb	5.5	5.6	5.7	5.7	5.7	5.7	5.5	5.4	5.1	4.8	4.5	4.1	3.7
Marc	5.6	5.6	5.5	5.5	5.3	5.2	4.9	4.7	4.4	4.1	3.7	3.3	2.9
April	5.4	5.3	5.1	4.9	4.7	4.4	4.1	3.8	3.4	3.1	2.7	2.3	1.9
May	5.1	4.9	4.6	4.4	4.1	3.7	3.4	3.0	2.6	2.2	1.8	1.4	1.0
June	4.9	4.7	4.4	4.1	3.7	3.4	3.0	2.6	2.2	1.8	1.4	1.0	0.6
July	5.0	4.8	4.5	4.2	3.9	3.5	3.1	2.8	2.4	2.0	1.6	1.2	0.7
Aug	5.3	5.1	4.9	4.7	4.4	4.1	3.8	3.4	3.1	2.7	2.3	1.9	1.5
Sept	5.5	5.4	5.3	5.2	5.0	4.8	4.6	4.3	4.0	3.7	3.3	2.9	2.5
Oct	5.5	5.6	5.6	5.6	5.6	5.5	5.3	5.1	4.9	4.6	4.2	3.9	3.4
Nov	5.4	5.5	5.7	5.8	5.8	5.8	5.7	5.6	5.4	5.2	4.9	4.5	4.0
Dec	5.2	5.5	5.7	5.8	5.9	5.9	5.9	5.8	5.6	5.4	5.1	4.7	4.2

Table B5: Global Radiation, H, kWh/m2 per day
based on Month's Daily Average of 7 Sunshine Hours

Latitude

	0	-5	-10	-15	-20	-25	-30	-35	-40	-45	-50	-55	-60
Jan	5.7	5.9	6.1	6.2	6.3	6.4	6.4	6.3	6.1	5.9	5.6	5.3	4.8
Feb	5.9	6.0	6.1	6.1	6.1	6.1	6.0	5.9	5.7	5.4	5.1	4.7	4.3
Marc	5.9	5.9	5.9	5.8	5.7	5.6	5.4	5.1	4.8	4.5	4.2	3.8	3.4
April	5.8	5.6	5.5	5.3	5.0	4.8	4.5	4.1	3.8	3.4	3.0	2.6	2.1
May	5.4	5.2	4.9	4.7	4.3	4.0	3.6	3.3	2.9	2.4	2.0	1.6	1.1
June	5.2	5.0	4.7	4.3	4.0	3.6	3.2	2.8	2.4	2.0	1.5	1.1	0.6
July	5.3	5.1	4.8	4.5	4.1	3.8	3.4	3.0	2.6	2.2	1.7	1.3	0.8
Aug	5.6	5.4	5.2	5.0	4.7	4.4	4.1	3.7	3.4	3.0	2.5	2.1	1.7
Sept	5.8	5.8	5.7	5.6	5.4	5.2	5.0	4.7	4.4	4.1	3.7	3.3	2.9
Oct	5.8	5.9	6.0	6.0	6.0	5.9	5.8	5.6	5.4	5.1	4.8	4.4	4.0
Nov	5.7	5.9	6.1	6.2	6.3	6.3	6.2	6.1	6.0	5.8	5.5	5.1	4.7
Dec	5.6	5.8	6.0	6.2	6.3	6.4	6.4	6.4	6.2	6.0	5.8	5.4	4.9

Table B6: Global Radiation, H, kWh/m2 per day
based on Month's Daily Average of 8 Sunshine Hours

Latitude

	0	-5	-10	-15	-20	-25	-30	-35	-40	-45	-50	-55	-60
Jan	5.9	6.2	6.4	6.6	6.7	6.8	6.8	6.8	6.7	6.5	6.2	5.9	5.4
Feb	6.2	6.3	6.4	6.5	6.5	6.5	6.4	6.3	6.1	5.9	5.6	5.3	4.8
Marc	6.2	6.2	6.2	6.2	6.1	5.9	5.7	5.5	5.3	4.9	4.6	4.2	3.8
April	6.0	5.9	5.7	5.5	5.3	5.0	4.8	4.4	4.1	3.7	3.3	2.8	2.4
May	5.7	5.5	5.2	4.9	4.6	4.2	3.9	3.5	3.1	2.6	2.2	1.7	1.2
June	5.5	5.2	4.9	4.6	4.2	3.8	3.4	3.0	2.6	2.1	1.7	1.2	0.6
July	5.6	5.3	5.0	4.7	4.3	4.0	3.6	3.2	2.8	2.3	1.9	1.4	0.9
Aug	5.9	5.7	5.5	5.2	5.0	4.7	4.3	4.0	3.6	3.2	2.8	2.3	1.8
Sept	6.1	6.1	6.0	5.9	5.7	5.5	5.3	5.1	4.8	4.4	4.0	3.6	3.2
Oct	6.1	6.2	6.3	6.3	6.3	6.3	6.2	6.0	5.8	5.6	5.3	4.9	4.5
Nov	6.0	6.2	6.4	6.5	6.6	6.7	6.7	6.6	6.5	6.3	6.1	5.7	5.3
Dec	5.9	6.1	6.4	6.6	6.7	6.8	6.9	6.9	6.8	6.6	6.4	6.0	5.5

Table C1: Auckland Airport

Latitude = -37.02 Degrees
Elevation = 0.008 km above sealevel
Regional Constant = 1.00

Month	Ho (kWh/m2)	Sunshine hours So	S	a	b	Hm	Hc	Percent error	Hc(adj)	Percent error
Jan	11.89	14.23	8.06	0.29	0.50	6.81	6.78	0.3	6.78	0.3
Feb	10.59	13.33	7.64	0.29	0.50	5.97	6.09	1.9	6.09	1.9
March	8.74	12.24	5.90	0.26	0.53	4.58	4.53	1.1	4.53	1.1
April	6.56	11.04	5.37	0.26	0.53	3.36	3.41	1.6	3.41	1.6
May	4.81	10.02	4.52	0.25	0.55	2.42	2.39	0.9	2.39	0.9
June	4.03	9.50	3.90	0.24	0.56	1.92	1.89	1.3	1.89	1.3
July	4.35	9.73	4.48	0.25	0.54	2.22	2.19	1.3	2.19	1.3
Aug	5.75	10.61	4.74	0.25	0.55	2.83	2.84	0.4	2.84	0.4
Sept	7.80	11.78	5.03	0.24	0.55	3.89	3.76	3.4	3.76	3.4
Oct	9.91	12.98	5.87	0.25	0.55	4.92	4.94	0.5	4.94	0.5
Nov	11.49	14.00	6.97	0.27	0.53	6.14	6.07	1.1	6.07	1.1
Dec	12.18	14.50	7.97	0.28	0.51	6.83	6.83	0.0	6.83	0.0
							MPE	1.1	MPE	1.1

Table C2: Alexandra

Latitude = -45.27 Degrees
Elevation = 0.141 km above sealevel
Regional Constant = 1.13

Month	Ho (kWh/m2)	Sunshine hours So	S	a	b	Hm	Hc	Percent error	Hc(adj)	Percent error
Jan	11.79	15.03	5.61	0.17	0.68	6.03	5.00	17.07	5.26	12.78
Feb	10.09	13.79	5.89	0.18	0.66	5.33	4.72	11.41	4.97	6.87
March	7.83	12.33	4.61	0.17	0.68	4.03	3.33	17.42	3.50	13.14
April	5.35	10.72	4.27	0.18	0.67	2.53	2.38	5.93	2.50	1.09
May	3.50	9.32	3.19	0.16	0.69	1.56	1.39	10.48	1.47	5.80
June	2.71	8.60	3.27	0.17	0.68	1.14	1.16	2.23	1.22	7.52
July	3.04	8.93	3.94	0.19	0.66	1.33	1.46	9.21	1.53	14.80
Aug	4.49	10.14	4.32	0.18	0.66	2.14	2.10	1.85	2.21	3.18
Sept	6.77	11.70	5.40	0.19	0.65	3.36	3.35	0.30	3.52	4.79
Oct	9.27	13.31	5.45	0.18	0.67	4.64	4.21	9.26	4.43	4.60
Nov	11.29	14.70	6.07	0.18	0.67	5.83	5.15	11.68	5.42	7.14
Dec	12.20	15.39	5.87	0.17	0.68	6.08	5.26	13.61	5.53	9.14
							MPE	9.2	MPE	7.5

Table C3 : Christchurch Airport

Latitude = -43.5 Degrees
Elevation = 0.0 km above sealevel
Regional Constant= 1.00

Month	Ho (kWh/m2)	Sunshine hours So	S	a	b	Hm	Hc	Percent error	Hc(adj)	Percent error
Jan	11.8	14.8	6.7	0.2	0.6	6.1	5.8	3.5	5.8	3.9
Feb	10.2	13.7	6.6	0.2	0.6	5.4	5.3	2.5	5.3	2.9
March	8.0	12.3	5.3	0.2	0.6	3.8	3.8	0.6	3.8	1.1
April	5.6	10.8	5.0	0.2	0.6	2.7	2.8	4.4	2.8	4.0
May	3.8	9.5	4.0	0.2	0.6	1.7	1.8	3.7	1.8	3.3
June	3.0	8.8	4.0	0.2	0.6	1.4	1.5	8.6	1.5	8.1
July	3.3	9.1	3.9	0.2	0.6	1.5	1.6	7.6	1.6	7.2
Aug	4.8	10.3	4.7	0.2	0.6	2.3	2.4	5.0	2.4	4.6
Sept	7.0	11.7	5.4	0.2	0.6	3.4	3.5	1.5	3.5	1.0
Oct	9.4	13.2	6.5	0.2	0.6	5.0	4.9	1.7	4.9	2.1
Nov	11.3	14.5	6.9	0.2	0.6	6.0	5.8	3.2	5.8	3.6
Dec	12.2	15.2	6.8	0.2	0.6	6.5	6.0	7.9	5.9	8.3
							MPE	4.2	MPE	4.2

Table C4: Dunedin Airport

Latitude = -45.9 Degrees
Elevation = 0.0 km above sealevel
Regional Constant= 1.00

Month	Ho (kWh/m2)	Sunshine hours So	S	a	b	Hm	Hc	Percent error	Hc(adj)	Percent error
Jan	11.8	15.1	5.6	0.2	0.7	5.6	5.0	10.6	5.0	10.6
Feb	10.0	13.8	5.9	0.2	0.7	4.9	4.7	2.8	4.7	2.8
March	7.8	12.3	4.6	0.2	0.7	3.5	3.3	5.9	3.3	5.9
April	5.2	10.7	4.3	0.2	0.7	2.3	2.4	1.0	2.4	1.0
May	3.4	9.3	3.2	0.2	0.7	1.4	1.4	3.3	1.4	3.3
June	2.6	8.5	3.3	0.2	0.7	1.1	1.1	2.3	1.1	2.3
July	2.9	8.9	3.9	0.2	0.7	1.3	1.4	13.9	1.4	13.9
Aug	4.4	10.1	4.3	0.2	0.7	2.0	2.1	3.6	2.1	3.6
Sept	6.7	11.7	5.4	0.2	0.6	3.2	3.3	3.3	3.3	3.3
Oct	9.2	13.3	5.5	0.2	0.7	4.4	4.2	4.2	4.2	4.2
Nov	11.3	14.8	6.1	0.2	0.7	5.6	5.2	7.5	5.2	7.5
Dec	12.2	15.5	5.9	0.2	0.7	6.0	5.3	11.7	5.3	11.7
							MPE	5.8	MPE	5.8

Table C5: Gisborne Airport

Latitude = -38.7 Degrees
Elevation = 0.0 km above sealevel
Regional Constant = 0.81

Month	Ho (kWh/m2)	Sunshine hours So	S	a	b	Hm	Hc	Percent error	Hc(adj)	Percent error
Jan	11.9	14.4	7.9	0.3	0.5	6.3	6.7	7.0	6.1	2.8
Feb	10.5	13.4	7.4	0.3	0.5	5.4	5.9	9.6	5.4	0.4
March	8.6	12.3	6.2	0.3	0.5	4.2	4.6	8.6	4.2	1.4
April	6.3	11.0	5.3	0.3	0.6	3.0	3.3	10.6	3.0	0.4
May	4.6	9.9	4.6	0.2	0.6	2.1	2.3	11.8	2.1	1.4
June	3.8	9.3	4.2	0.2	0.6	1.6	1.9	16.3	1.7	5.5
July	4.1	9.6	4.3	0.2	0.6	1.9	2.0	7.0	1.8	3.0
Aug	5.5	10.5	4.7	0.2	0.6	2.5	2.7	8.0	2.5	2.0
Sept	7.6	11.8	5.9	0.3	0.5	3.8	4.0	6.5	3.7	3.3
Oct	9.8	13.0	6.7	0.3	0.5	5.0	5.3	5.4	4.8	4.3
Nov	11.5	14.1	7.6	0.3	0.5	6.1	6.3	4.2	5.8	5.4
Dec	12.2	14.7	7.7	0.3	0.5	6.4	6.7	4.3	6.1	5.2
							MPE	8.3	MPE	3.0

Table C6: Hokitika Airport

Latitude = -42.7 Degrees
Elevation = 0.0 km above sealevel
Regional Constant = 0.88

Month	Ho (kWh/m2)	Sunshine hours So	S	a	b	Hm	Hc	Percent error	Hc(adj)	Percent error
Jan	11.8	14.8	6.1	0.2	0.6	5.7	5.5	4.5	5.2	9.5
Feb	10.3	13.6	6.6	0.2	0.6	5.2	5.3	1.7	5.0	3.6
March	8.1	12.3	5.1	0.2	0.6	3.8	3.8	1.1	3.6	4.2
April	5.7	10.8	4.5	0.2	0.6	2.5	2.7	7.4	2.5	1.7
May	3.9	9.6	3.9	0.2	0.6	1.6	1.8	14.1	1.7	8.1
June	3.1	8.9	3.9	0.2	0.6	1.3	1.5	19.5	1.4	13.2
July	3.4	9.2	3.9	0.2	0.6	1.4	1.6	14.8	1.5	8.7
Aug	4.9	10.3	4.5	0.2	0.6	2.2	2.4	9.4	2.2	3.7
Sept	7.1	11.7	4.8	0.2	0.6	3.1	3.3	4.7	3.1	0.9
Oct	9.5	13.2	5.2	0.2	0.6	4.2	4.3	1.2	4.0	4.2
Nov	11.4	14.5	5.8	0.2	0.6	5.4	5.2	5.2	4.9	10.2
Dec	12.2	15.1	6.5	0.2	0.6	5.9	5.8	0.4	5.5	5.7
							MPE	7.0	MPE	6.1

Table C7: Invercargill

Latitude = -46.4 Degrees
Elevation = 0.000 km above sealevel
Regional Constant = 1.35

Month	Ho (kWh/m2)	Sunshine hours So	S	a	b	Hm	Hc	Percent error	Hc(adj)	Percent error
Jan	11.8	15.2	6.0	0.2	0.7	5.9	5.26	10.3	5.99	2.2
Feb	10.0	13.9	5.8	0.2	0.7	5.1	4.65	8.5	5.30	4.2
March	7.7	12.3	4.5	0.2	0.7	3.6	3.25	8.6	3.71	4.3
April	5.2	10.7	3.4	0.2	0.7	2.2	1.96	10.5	2.24	2.3
May	3.3	9.2	2.8	0.2	0.7	1.4	1.23	9.7	1.40	3.2
June	2.5	8.5	2.4	0.1	0.7	1.1	0.87	17.3	1.00	5.2
July	2.9	8.8	3.0	0.2	0.7	1.3	1.13	9.4	1.29	3.4
Aug	4.3	10.1	3.9	0.2	0.7	2.1	1.88	8.5	2.14	4.3
Sept	6.6	11.7	4.6	0.2	0.7	3.2	2.92	10.3	3.32	2.3
Oct	9.2	13.4	5.2	0.2	0.7	4.5	4.01	11.4	4.57	1.0
Nov	11.2	14.8	5.7	0.2	0.7	5.6	4.93	12.2	5.61	0.0
Dec	12.2	15.5	6.1	0.2	0.7	6.2	5.37	12.9	6.12	0.7
							MPE	10.8	MPE	2.8

Table C8: Kaikoura

Latitude = -42.4 Degrees
Elevation = 0.108 km above sealevel
Regional Constant = 0.94

Month	Ho (kWh/m2)	Sunshine hours So	S	a	b	Hm	Hc	Percent error	Hc(adj)	Percent error
Jan	11.8	14.7	6.9	0.2	0.6	6.4	5.94	7.4	5.79	9.8
Feb	10.3	13.6	6.9	0.2	0.6	5.7	5.46	4.2	5.32	6.7
March	8.2	12.3	5.4	0.2	0.6	4.1	3.93	5.1	3.82	7.6
April	5.8	10.8	5.3	0.2	0.6	2.9	2.98	3.2	2.90	0.5
May	4.0	9.6	4.2	0.2	0.6	1.9	1.91	2.7	1.86	0.0
June	3.2	8.9	4.1	0.2	0.6	1.5	1.57	6.6	1.53	3.8
July	3.5	9.2	4.9	0.2	0.6	1.7	1.91	14.8	1.86	11.9
Aug	4.9	10.3	5.2	0.2	0.6	2.4	2.60	8.7	2.53	5.9
Sept	7.1	11.7	7.0	0.3	0.6	3.6	4.22	17.0	4.12	14.0
Oct	9.5	13.2	6.8	0.2	0.6	5.1	5.11	0.5	4.98	3.0
Nov	11.4	14.4	6.9	0.2	0.6	6.2	5.79	7.0	5.64	9.4
Dec	12.2	15.1	6.6	0.2	0.6	6.7	5.90	12.2	5.75	14.5
							MPE	7.4	MPE	7.2

Table C9: Kaitai Airport

Latitude = -35.1 Degrees
Elevation = 0.1 km above sealevel
Regional Constant = 0.93

Month	Ho (kWh/m	Sunshine hours So	S	a	b	Hm	Hc	Percent error	Hc(adj)	Percent error
Jan	11.9	14.1	7.5	0.3	0.5	6.4	6.5	2.5	6.3	1.2
Feb	10.7	13.2	6.8	0.3	0.5	5.4	5.7	7.2	5.5	3.4
March	8.9	12.2	5.8	0.3	0.5	4.4	4.6	4.7	4.4	0.9
April	6.8	11.1	5.4	0.3	0.5	3.3	3.6	6.8	3.4	3.0
May	5.1	10.2	4.8	0.3	0.5	2.5	2.6	5.9	2.5	2.1
June	4.3	9.7	4.2	0.3	0.5	2.0	2.1	5.9	2.0	2.0
July	4.7	9.9	4.6	0.3	0.5	2.3	2.4	4.2	2.3	0.4
Aug	6.0	10.7	5.0	0.3	0.5	2.9	3.1	5.9	2.9	2.1
Sept	8.0	11.8	5.6	0.3	0.5	4.0	4.1	2.5	4.0	1.2
Oct	10.0	12.9	5.9	0.3	0.5	4.9	5.0	3.3	4.9	0.5
Nov	11.5	13.9	6.7	0.3	0.5	5.7	6.0	4.3	5.8	0.6
Dec	12.2	14.3	7.0	0.3	0.5	6.4	6.3	1.2	6.1	4.7
							MPE	4.5	MPE	1.8

Table C10: Kelburn

Latitude = -41.3 Degrees
Elevation = 0.1 km above sealevel
Regional Constant = 0.91

Month	Ho (kWh/m	Sunshine hours So	S	a	b	Hm	Hc	Percent error	Hc(adj)	Percent error
Jan	11.9	14.6	7.6	0.2	0.6	6.5	6.4	1.8	6.2	5.7
Feb	10.4	13.6	7.2	0.2	0.6	5.6	5.7	1.9	5.4	2.2
March	8.3	12.3	6.0	0.2	0.6	4.1	4.3	3.8	4.1	0.4
April	5.9	10.9	5.0	0.2	0.6	2.9	3.0	3.8	2.9	0.4
May	4.1	9.7	3.8	0.2	0.6	1.8	1.9	2.5	1.8	1.6
June	3.3	9.1	3.5	0.2	0.6	1.4	1.5	1.6	1.4	2.5
July	3.7	9.3	4.3	0.2	0.6	1.5	1.8	18.9	1.7	14.1
Aug	5.1	10.4	5.2	0.2	0.6	2.3	2.7	19.9	2.6	15.1
Sept	7.3	11.7	6.3	0.2	0.6	3.5	4.0	14.2	3.9	9.7
Oct	9.6	13.1	6.7	0.2	0.6	4.9	5.1	4.2	4.9	0.1
Nov	11.4	14.3	7.5	0.2	0.6	5.9	6.2	4.2	5.9	0.1
Dec	12.2	14.9	7.2	0.2	0.6	6.4	6.3	1.6	6.0	5.5
							MPE	6.5	MPE	4.8

Table C11: Leigh

Latitude = -36.7 Degrees
Elevation = 0.0 km above sealevel
Regional Constant = 1.03

Month	Ho (kWh/m2)	Sunshine hours So	S	a	b	Hm	Hc	Percent error	Hc(adj)	Percent error
Jan	11.9	14.2	7.8	0.3	0.5	7.0	6.6	5.5	6.7	4.1
Feb	10.6	13.3	7.3	0.3	0.5	6.2	5.9	4.7	6.0	3.3
March	8.8	12.2	5.6	0.3	0.5	4.8	4.4	6.8	4.5	5.4
April	6.6	11.1	5.2	0.3	0.5	3.4	3.4	2.1	3.4	0.7
May	4.9	10.0	4.7	0.3	0.5	2.4	2.5	5.0	2.5	6.6
June	4.1	9.5	3.9	0.2	0.6	1.7	1.9	11.1	1.9	12.8
July	4.4	9.8	4.6	0.3	0.5	2.1	2.2	9.2	2.3	10.9
Aug	5.8	10.6	4.9	0.3	0.5	2.9	2.9	1.1	3.0	0.4
Sept	7.8	11.8	5.2	0.3	0.5	4.0	3.9	4.0	3.9	2.5
Oct	9.9	13.0	5.9	0.3	0.5	5.1	5.0	2.9	5.1	1.5
Nov	11.5	14.0	6.9	0.3	0.5	6.3	6.0	4.8	6.1	3.4
Dec	12.2	14.5	7.4	0.3	0.5	7.4	6.5	11.3	6.6	9.9
							MPE	5.7	MPE	5.1

Table C12: Levin

Latitude = -40.7 Degrees
Elevation = 0.0 km above sealevel
Regional Constant = 1.13

Month	Ho (kWh/m2)	Sunshine hours So	S	a	b	Hm	Hc	Percent error	Hc(adj)	Percent error
Jan	11.9	14.6	6.8	0.2	0.6	6.3	6.0	4.3	6.3	1.4
Feb	10.4	13.5	6.9	0.2	0.6	5.6	5.5	1.8	5.9	4.1
March	8.4	12.3	5.5	0.2	0.6	4.1	4.1	0.1	4.3	6.1
April	6.0	10.9	4.9	0.2	0.6	3.0	3.0	0.5	3.2	6.5
May	4.2	9.7	3.8	0.2	0.6	2.0	1.9	5.6	2.0	0.2
June	3.4	9.1	3.6	0.2	0.6	1.7	1.5	10.2	1.6	4.8
July	3.8	9.4	3.7	0.2	0.6	1.9	1.7	7.8	1.8	2.2
Aug	5.2	10.4	4.1	0.2	0.6	2.6	2.3	8.2	2.5	2.6
Sept	7.4	11.7	4.6	0.2	0.6	3.4	3.3	3.4	3.5	2.5
Oct	9.7	13.1	5.2	0.2	0.6	4.7	4.4	6.4	4.7	0.7
Nov	11.4	14.3	5.9	0.2	0.6	5.8	5.3	7.4	5.6	1.8
Dec	12.2	14.9	6.4	0.2	0.6	6.4	5.9	9.1	6.2	3.6
							MPE	5.4	MPE	3.0

Table C13: Nelson Airport

Latitude = -41.3 Degrees
Elevation = 0.0 km above sealevel
Regional Constant = 0.82

Month	Ho (kWh/m2)	Sunshine hours So	S	a	b	Hm	Hc	Percent error	Hc(adj)	Percent error
Jan	11.9	14.6	*	0.1	0.8	7.0	NA	NA	NA	NA
Feb	10.4	13.6	9.3	0.3	0.5	6.1	6.7	8.6	6.1	0.4
March	8.3	12.3	7.2	0.3	0.5	4.5	4.9	8.5	4.5	0.4
April	5.9	10.9	7.0	0.3	0.5	3.1	3.7	20.2	3.4	10.4
May	4.1	9.7	6.0	0.3	0.5	2.1	2.5	20.3	2.3	10.5
June	3.3	9.1	5.5	0.3	0.5	1.6	2.0	25.8	1.8	15.5
July	3.7	9.3	4.8	0.2	0.6	1.8	2.0	11.3	1.8	2.2
Aug	5.1	10.4	5.1	0.2	0.6	2.5	2.7	8.4	2.5	0.5
Sept	7.3	11.7	5.6	0.2	0.6	3.8	3.8	0.7	3.4	8.9
Oct	9.6	13.1	6.2	0.2	0.6	5.2	4.9	6.6	4.5	14.2
Nov	11.4	14.3	7.2	0.2	0.6	6.4	6.0	5.6	5.5	13.3
Dec	12.2	14.9	7.3	0.2	0.6	6.9	6.4	8.4	5.8	15.9
							MPE	11.3	MPE	8.4

* = no data available
NA = not applicable

Table C14: Ohakea

Latitude = -40.2 Degrees
Elevation = 0.0 km above sealevel
Regional Constant = 1.0

Month	Ho (kWh/m2)	Sunshine hours So	S	a	b	Hm	Hc	Percent error	Hc(adj)	Percent error
Jan	11.9	14.5	7.8	0.3	0.6	6.8	6.6	3.9	6.6	3.9
Feb	10.4	13.5	7.6	0.3	0.5	6.0	5.9	0.6	5.9	0.6
March	8.4	12.3	6.0	0.2	0.6	4.4	4.4	1.8	4.4	1.8
April	6.1	10.9	5.3	0.2	0.6	3.2	3.2	0.2	3.2	0.2
May	4.3	9.8	4.1	0.2	0.6	2.1	2.0	2.1	2.0	2.1
June	3.5	9.2	3.7	0.2	0.6	1.6	1.6	1.5	1.6	1.5
July	3.8	9.5	4.4	0.2	0.6	1.8	1.9	7.7	1.9	7.7
Aug	5.3	10.4	5.1	0.2	0.6	2.6	2.7	5.6	2.7	5.6
Sept	7.4	11.8	6.4	0.3	0.6	3.8	4.1	9.2	4.1	9.2
Oct	9.7	13.1	6.8	0.3	0.6	5.1	5.2	3.7	5.2	3.7
Nov	11.4	14.2	7.6	0.3	0.6	6.3	6.3	0.5	6.3	0.5
Dec	12.2	14.8	7.3	0.2	0.6	6.8	6.4	6.3	6.4	6.3
							MPE	3.6	MPE	3.6

Table C15: Rukuhia

Latitude = -37.8 Degrees
Elevation = 0.1 km above sealevel
Regional Constant = 1.02

Month	Ho (kWh/m2)	Sunshine hours So	S	a	b	Hm	Hc	Percent error	Hc(adj)	Percent error
Jan	11.9	14.3	7.4	0.3	0.5	6.3	6.4	2.5	6.4	2.5
Feb	10.6	13.4	6.9	0.3	0.5	5.6	5.7	1.9	5.7	1.9
March	8.7	12.3	5.7	0.2	0.6	4.4	4.4	0.2	4.4	0.2
April	6.4	11.0	5.2	0.2	0.6	3.3	3.3	1.0	3.3	1.0
May	4.7	10.0	4.0	0.2	0.6	2.2	2.2	1.7	2.2	1.7
June	3.9	9.4	3.5	0.2	0.6	1.8	1.7	2.4	1.7	2.4
July	4.2	9.7	3.9	0.2	0.6	2.0	2.0	1.9	2.0	1.9
Aug	5.6	10.6	4.3	0.2	0.6	2.7	2.6	1.7	2.6	1.7
Sept	7.7	11.8	5.1	0.2	0.6	3.7	3.7	0.4	3.7	0.4
Oct	9.9	13.0	5.6	0.2	0.6	4.9	4.8	2.3	4.8	2.3
Nov	11.5	14.1	6.7	0.3	0.6	5.9	5.9	0.0	5.9	0.0
Dec	12.2	14.6	6.9	0.2	0.6	6.4	6.2	3.2	6.2	3.2
							MPE	1.6	MPE	1.6

Table C16: Whenuapai

Latitude = -36.8 Degrees
Elevation = 0.0 km above sealevel
Regional Constant = 1.04

Month	Ho (kWh/m2)	Sunshine hours So	S	a	b	Hm	Hc	Percent error	Hc(adj)	Percent error
Jan	11.9	14.2	7.2	0.3	0.5	6.4	6.3	1.2	6.5	0.8
Feb	10.6	13.3	6.8	0.3	0.5	5.8	5.7	2.0	5.8	0.1
March	8.8	12.2	5.9	0.3	0.5	4.8	4.5	4.7	4.6	2.8
April	6.6	11.1	5.3	0.3	0.5	3.5	3.4	2.4	3.5	0.5
May	4.8	10.0	4.2	0.2	0.6	2.4	2.3	2.5	2.3	0.5
June	4.1	9.5	3.8	0.2	0.6	1.9	1.9	4.1	1.9	2.1
July	4.4	9.8	4.2	0.2	0.6	2.2	2.1	5.1	2.2	3.1
Aug	5.8	10.6	4.8	0.3	0.5	2.9	2.9	1.1	3.0	3.1
Sept	7.8	11.8	5.5	0.3	0.5	4.0	4.0	0.5	4.1	2.5
Oct	9.9	13.0	6.1	0.3	0.5	5.1	5.1	0.4	5.2	1.7
Nov	11.5	14.0	6.8	0.3	0.5	5.9	6.0	1.0	6.1	3.1
Dec	12.2	14.5	7.1	0.3	0.5	6.4	6.4	0.0	6.5	2.0
							MPE	2.1	MPE	1.9

Appendix D: Summary of Measured Daily Radiation per Month for Various Locations in New Zealand

Radiation (H, kWh/m2/day)

Location	Latitude	Jan	Feb	March	April	May	June	July	Aug	Sept	Oct	Nov	Dec
Alexandra	-45.27	6.0	5.3	4.0	2.5	1.6	1.1	1.3	2.1	3.4	4.6	5.8	6.1
Auckland AP	-37.01	6.8	6.0	4.6	3.4	2.4	1.9	2.2	2.8	3.9	4.9	6.1	6.8
Christchurch AP	-43.48	6.1	5.4	3.8	2.7	1.7	1.4	1.5	2.3	3.4	5.0	6.0	6.5
Dunedin AP	-45.93	5.6	4.9	3.5	2.3	1.4	1.1	1.3	2.0	3.2	4.4	5.6	6.0
Gisborne AP	-38.67	6.3	5.4	4.2	3.0	2.1	1.6	1.9	2.5	3.8	5.0	6.1	6.4
Hokitika	-42.72	5.7	5.2	3.8	2.5	1.6	1.3	1.4	2.2	3.1	4.2	5.4	5.9
Invercargill	-46.42	5.9	5.1	3.6	2.2	1.4	1.1	1.3	2.1	3.2	4.5	5.6	6.2
Kaikoura	-42.42	6.4	5.7	4.1	2.9	1.9	1.5	1.7	2.4	3.6	5.1	6.2	6.7
Kaitai	-35.07	6.4	5.4	4.4	3.3	2.5	2.0	2.3	2.9	4.0	4.9	5.7	6.4
Kelburn	-41.28	6.5	5.4	4.4	3.3	2.5	2.0	2.3	2.9	4.0	4.9	5.7	6.4
Leigh	-36.67	7.0	6.2	4.8	3.4	2.4	1.7	2.1	2.9	4.0	5.1	6.3	7.4
Levin	-40.65	6.3	5.6	4.1	3.0	2.0	1.7	1.9	2.6	3.4	4.7	5.8	6.4
Mt.John	-43.98	6.9	6.1	4.5	3.1	2.1	1.7	1.8	2.7	3.9	5.3	6.7	7.0
Nelson AP	-41.28	7.0	6.1	4.5	3.1	2.1	1.6	1.8	2.5	3.8	5.2	6.4	6.9
Ohakea	-40.20	6.8	6.0	4.4	3.2	2.1	1.6	1.8	2.6	3.8	5.1	6.3	6.8
Puketura *	-35.67	6.2	5.0	4.1	3.2	2.4	1.9	2.2	2.9	3.9	4.8	5.7	6.2
Rotorua AP *	-38.12	6.4	5.6	4.5	3.4	2.4	1.9	2.3	2.9	3.8	5.1	6.1	6.5
Rukuhia	-37.83	6.3	5.6	4.4	3.3	2.2	1.8	2.0	2.7	3.7	4.9	5.9	6.4
Whenuapai	-36.78	6.4	5.8	4.8	3.5	2.4	1.9	2.2	2.9	4.0	5.1	5.9	6.4
Winchmore *	-43.80	6.7	5.8	4.2	2.9	1.8	1.5	1.6	2.4	3.7	5.3	6.4	7.0

AP = Airport
* = No sunshine duration information available

Appendix E: Radiation on a Tilted Surface, Ht (kWh/m ^{2} per day), based on Latitude, Tilt Angle and H

Table E1

Latitude= -30.0
Tilt = 20.0 H (kWh/m2)

	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5	8.0
Jan	0.9	1.5	1.9	2.4	2.9	3.4	3.8	4.3	4.7	5.2	5.7	6.1	6.5	7.0	7.4
Feb	1.0	1.5	1.9	2.4	2.9	3.4	3.9	4.4	4.9	5.4	5.9	6.4	6.9	7.4	7.9
Marc	1.0	1.5	2.0	2.5	3.0	3.5	4.1	4.7	5.2	5.8	6.5	7.1	7.6	8.2	8.7
April	1.0	1.5	2.0	2.6	3.2	3.9	4.6	5.3	6.1	6.4	7.3	8.0	8.5	9.3	9.8
May	1.0	1.5	2.2	2.9	3.7	4.5	5.5	5.8	6.8	7.0	8.1	9.0	9.4	10.4	10.9
June	1.0	1.6	2.3	3.1	4.0	5.1	5.8	6.1	7.2	7.4	8.5	9.6	9.9	11.1	11.6
July	1.0	1.6	2.3	3.0	3.9	4.9	5.6	6.0	7.0	7.2	8.3	9.3	9.7	10.8	11.3
Aug	1.0	1.5	2.1	2.7	3.4	4.1	4.9	5.8	6.4	6.7	7.6	8.4	8.8	9.7	10.2
Sept	1.0	1.5	2.0	2.5	3.1	3.6	4.3	4.9	5.5	6.2	6.9	7.4	7.9	8.6	9.1
Oct	1.0	1.5	2.0	2.4	2.9	3.4	4.0	4.5	5.0	5.5	6.1	6.6	7.1	7.7	8.2
Nov	1.0	1.4	1.9	2.4	2.9	3.4	3.8	4.3	4.8	5.2	5.7	6.2	6.6	7.1	7.5
Dec	1.0	1.4	1.9	2.4	2.9	3.3	3.8	4.3	4.7	5.2	5.6	6.0	6.5	6.9	7.3

Table E2

Latitude= -30.0
Tilt = 30.0 H (kWh/m2)

	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5	8.0
Jan	0.9	1.4	1.8	2.3	2.8	3.2	3.6	4.1	4.5	4.9	5.3	5.7	6.1	6.5	6.8
Feb	0.9	1.4	1.9	2.3	2.8	3.3	3.8	4.2	4.7	5.2	5.7	6.1	6.6	7.1	7.6
Marc	0.9	1.4	1.9	2.4	2.9	3.5	4.0	4.6	5.2	5.8	6.5	7.1	7.5	8.2	8.7
April	0.9	1.5	2.0	2.6	3.2	4.0	4.7	5.5	6.4	6.6	7.6	8.5	8.8	9.8	10.2
May	1.0	1.5	2.2	3.0	3.9	4.9	6.0	6.3	7.5	7.5	8.8	9.9	10.2	11.4	11.9
June	1.0	1.6	2.4	3.3	4.4	5.6	6.5	6.7	8.1	8.0	9.5	10.8	11.0	12.4	12.9
July	1.0	1.6	2.3	3.1	4.1	5.3	6.2	6.5	7.8	7.8	9.1	10.4	10.6	12.0	12.4
Aug	1.0	1.5	2.1	2.7	3.5	4.3	5.2	6.1	6.8	7.0	8.0	9.0	9.4	10.4	10.9
Sept	1.0	1.4	1.9	2.5	3.0	3.6	4.2	4.9	5.5	6.3	7.0	7.6	8.0	8.8	9.2
Oct	0.9	1.4	1.9	2.4	2.8	3.3	3.8	4.3	4.8	5.3	5.9	6.4	6.9	7.4	7.9
Nov	0.9	1.4	1.9	2.3	2.8	3.2	3.7	4.1	4.5	5.0	5.4	5.8	6.2	6.6	7.0
Dec	0.9	1.4	1.8	2.3	2.8	3.2	3.6	4.0	4.4	4.9	5.2	5.6	6.0	6.3	6.7

Table E3

Latitude= -30.0
Tilt = 40.0 H (kWh/m2)

	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5	8.0
Jan	0.8	1.3	1.7	2.2	2.6	3.0	3.4	3.8	4.1	4.5	4.9	5.2	5.5	5.8	6.1
Feb	0.9	1.3	1.8	2.2	2.6	3.1	3.5	4.0	4.4	4.8	5.3	5.7	6.1	6.6	7.0
Marc	0.9	1.3	1.8	2.3	2.8	3.3	3.8	4.4	5.0	5.6	6.3	6.9	7.3	8.0	8.4
April	0.9	1.4	1.9	2.5	3.2	3.9	4.7	5.5	6.5	6.7	7.7	8.7	9.0	10.0	10.4
May	0.9	1.5	2.2	3.0	4.0	5.1	6.3	6.5	7.9	7.8	9.2	10.5	10.7	12.1	12.6
June	1.0	1.6	2.5	3.4	4.6	6.1	6.9	7.1	8.7	8.4	10.1	11.6	11.8	13.4	13.8
July	1.0	1.5	2.3	3.2	4.3	5.7	6.6	6.8	8.3	8.1	9.7	11.1	11.3	12.8	13.2
Aug	1.0	1.4	2.0	2.7	3.5	4.4	5.3	6.4	7.1	7.1	8.3	9.4	9.7	10.8	11.3
Sept	0.9	1.4	1.8	2.4	2.9	3.5	4.1	4.8	5.4	6.2	7.0	7.5	7.9	8.7	9.1
Oct	0.9	1.3	1.8	2.2	2.7	3.1	3.6	4.1	4.5	5.0	5.5	6.0	6.5	7.0	7.4
Nov	0.9	1.3	1.7	2.2	2.6	3.0	3.4	3.8	4.2	4.6	4.9	5.3	5.7	6.0	6.3
Dec	0.9	1.3	1.7	2.2	2.6	3.0	3.4	3.7	4.1	4.4	4.7	5.1	5.4	5.6	5.9

Table E4

Latitude= -30.0
Tilt = 50.0 H (kWh/m2)

	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5	8.0
Jan	0.7	1.2	1.6	2.0	2.4	2.7	3.1	3.4	3.7	4.0	4.3	4.6	4.8	5.0	5.3
Feb	0.8	1.2	1.6	2.0	2.4	2.8	3.2	3.6	4.0	4.4	4.8	5.1	5.5	5.9	6.3
Marc	0.8	1.2	1.7	2.1	2.6	3.1	3.6	4.1	4.7	5.2	5.9	6.5	6.9	7.5	7.9
April	0.8	1.3	1.8	2.4	3.1	3.8	4.6	5.4	6.5	6.5	7.6	8.6	8.9	9.9	10.3
May	0.8	1.4	2.1	3.0	4.0	5.2	6.4	6.6	8.1	7.9	9.4	10.8	11.0	12.4	12.9
June	0.9	1.6	2.5	3.4	4.8	6.3	7.2	7.3	9.0	8.7	10.5	12.1	12.2	13.9	14.4
July	0.9	1.5	2.3	3.2	4.4	5.8	6.8	7.0	8.6	8.3	10.0	11.5	11.6	13.2	13.7
Aug	0.9	1.4	1.9	2.6	3.4	4.3	5.2	6.4	7.1	7.1	8.3	9.5	9.7	10.9	11.3
Sept	0.9	1.3	1.7	2.2	2.7	3.3	3.9	4.5	5.2	6.0	6.7	7.2	7.6	8.4	8.8
Oct	0.8	1.2	1.6	2.1	2.5	2.9	3.3	3.7	4.2	4.6	5.0	5.5	5.9	6.3	6.8
Nov	0.8	1.2	1.6	2.0	2.4	2.8	3.1	3.4	3.8	4.1	4.4	4.7	5.0	5.2	5.4
Dec	0.8	1.2	1.6	2.0	2.4	2.7	3.1	3.4	3.7	4.0	4.2	4.4	4.7	4.8	5.0

Table E5

Latitude= -35.0
Tilt = 25.0 H (kWh/m2)

	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5	8.0
Jan	0.9	1.4	1.9	2.4	2.8	3.3	3.8	4.2	4.7	5.1	5.6	6.0	6.5	6.9	7.4
Feb	1.0	1.4	1.9	2.4	2.9	3.4	3.9	4.4	4.9	5.4	5.9	6.5	7.0	7.5	8.0
Marc	1.0	1.4	2.0	2.5	3.0	3.6	4.2	4.8	5.4	6.1	6.8	7.1	7.8	8.6	9.0
April	1.0	1.5	2.1	2.7	3.4	4.1	5.0	5.9	6.1	7.0	7.9	8.1	9.1	10.1	10.5
May	1.0	1.6	2.4	3.3	4.2	5.4	5.6	6.8	6.8	8.1	9.2	9.2	10.5	11.8	12.2
June	1.0	1.7	2.6	3.8	5.1	5.8	6.0	7.3	7.2	8.7	10.0	9.9	11.3	12.8	13.3
July	1.0	1.7	2.5	3.5	4.7	5.6	5.8	7.1	7.0	8.4	9.6	9.6	10.9	12.3	12.8
Aug	1.0	1.5	2.1	2.9	3.7	4.6	5.5	6.2	6.4	7.4	8.4	8.6	9.6	10.7	11.2
Sept	1.0	1.5	2.0	2.5	3.1	3.7	4.4	5.1	5.9	6.6	7.2	7.5	8.3	9.1	9.6
Oct	1.0	1.5	1.9	2.4	2.9	3.4	4.0	4.5	5.0	5.6	6.1	6.7	7.3	7.8	8.3
Nov	1.0	1.4	1.9	2.4	2.9	3.3	3.8	4.3	4.7	5.2	5.7	6.1	6.6	7.1	7.5
Dec	1.0	1.4	1.9	2.4	2.8	3.3	3.8	4.2	4.7	5.1	5.5	6.0	6.4	6.8	7.2

Table E6

Latitude= -35.0
Tilt = 35.0 H (kWh/m2)

	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5	8.0
Jan	0.9	1.4	1.8	2.3	2.7	3.1	3.6	4.0	4.4	4.8	5.2	5.6	6.0	6.4	6.8
Feb	0.9	1.4	1.8	2.3	2.8	3.2	3.7	4.2	4.7	5.2	5.7	6.2	6.7	7.2	7.6
Marc	0.9	1.4	1.9	2.4	2.9	3.5	4.1	4.7	5.3	6.1	6.8	7.1	7.8	8.5	9.0
April	0.9	1.5	2.0	2.7	3.5	4.2	5.1	6.1	6.2	7.3	8.3	8.4	9.5	10.6	11.1
May	1.0	1.6	2.5	3.5	4.5	5.9	6.0	7.3	7.2	8.7	10.0	9.9	11.4	12.9	13.3
June	1.0	1.8	2.8	4.1	5.7	6.5	6.5	8.1	7.8	9.6	11.1	10.8	12.6	14.3	14.7
July	1.0	1.7	2.6	3.7	5.2	6.2	6.3	7.7	7.5	9.2	10.6	10.4	12.0	13.6	14.1
Aug	1.0	1.5	2.1	3.0	3.8	4.8	5.9	6.6	6.6	7.9	9.0	9.0	10.2	11.5	11.9
Sept	1.0	1.4	1.9	2.5	3.1	3.7	4.4	5.1	5.9	6.7	7.3	7.5	8.4	9.3	9.7
Oct	0.9	1.4	1.8	2.3	2.8	3.3	3.8	4.3	4.9	5.4	5.9	6.5	7.1	7.6	8.0
Nov	0.9	1.4	1.8	2.3	2.7	3.2	3.6	4.0	4.5	4.9	5.3	5.7	6.2	6.6	7.0
Dec	0.9	1.3	1.8	2.2	2.7	3.1	3.5	4.0	4.4	4.8	5.1	5.5	5.9	6.2	6.6

Table E7

Latitude= -35.0
Tilt = 45.0
H (kWh/m2)

	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5	8.0
Jan	5.1	1.3	1.7	2.1	2.5	2.9	3.3	3.7	4.0	4.4	4.8	5.1	5.4	5.8	6.1
Feb	6.5	1.3	1.7	2.1	2.6	3.0	3.5	3.9	4.4	4.8	5.3	5.7	6.2	6.6	7.1
Mar	8.8	1.3	1.8	2.2	2.7	3.3	3.9	4.5	5.1	5.9	6.5	6.8	7.6	8.3	8.7
Apri	12.8	1.4	2.0	2.6	3.4	4.2	5.2	6.2	6.2	7.4	8.5	8.5	9.7	10.8	11.3
May	17.8	1.6	2.5	3.6	4.7	6.2	6.2	7.7	7.5	9.2	10.6	10.3	12.0	13.6	14.1
Jun	21.2	1.8	2.9	4.4	6.2	6.9	6.9	8.7	8.2	10.2	11.9	11.4	13.4	15.4	15.8
July	19.6	1.7	2.7	3.9	5.5	6.6	6.6	8.2	7.8	9.7	11.3	10.9	12.7	14.6	15.0
Aug	14.7	1.4	2.1	2.9	3.9	4.9	6.0	6.8	6.7	8.1	9.3	9.2	10.6	11.9	12.3
Sep	10.2	1.4	1.8	2.3	2.9	3.6	4.3	5.0	5.8	6.6	7.2	7.4	8.3	9.2	9.6
Oct	7.1	1.3	1.7	2.2	2.6	3.1	3.6	4.1	4.6	5.1	5.6	6.1	6.6	7.1	7.6
Nov	5.4	1.3	1.7	2.1	2.5	2.9	3.3	3.7	4.1	4.5	4.9	5.2	5.6	5.9	6.3
Dec	4.9	1.2	1.7	2.1	2.5	2.9	3.3	3.6	4.0	4.3	4.6	5.0	5.3	5.5	5.9

Table E8

Latitude= -35.0
Tilt = 55.0
H (kWh/m2)

	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5	8.0
Jan	0.7	1.2	1.5	1.9	2.3	2.6	3.0	3.3	3.6	3.9	4.2	4.5	4.7	5.0	5.2
Feb	0.8	1.2	1.6	2.0	2.4	2.8	3.2	3.5	3.9	4.3	4.7	5.1	5.5	5.9	6.3
Mar	0.8	1.2	1.6	2.1	2.5	3.1	3.6	4.2	4.8	5.5	6.2	6.4	7.1	7.8	8.2
Apri	0.8	1.3	1.9	2.5	3.3	4.1	5.1	6.1	6.1	7.3	8.4	8.3	9.5	10.7	11.1
May	0.9	1.5	2.4	3.6	4.8	6.3	6.3	7.9	7.5	9.3	10.8	10.4	12.2	14.0	14.4
Jun	1.0	1.8	2.9	4.5	6.4	7.2	7.1	9.0	8.3	10.5	12.3	11.7	13.9	16.0	16.4
July	0.9	1.6	2.6	3.9	5.6	6.8	6.7	8.5	8.0	10.0	11.6	11.1	13.1	15.1	15.5
Aug	0.9	1.4	2.0	2.9	3.8	4.9	6.1	6.8	6.6	8.1	9.3	9.1	10.6	12.0	12.4
Sep	0.8	1.3	1.7	2.2	2.8	3.4	4.1	4.7	5.6	6.4	6.9	7.1	8.0	8.8	9.2
Oct	0.8	1.2	1.6	2.0	2.4	2.8	3.3	3.7	4.2	4.6	5.1	5.6	6.0	6.5	6.9
Nov	0.8	1.2	1.5	1.9	2.3	2.7	3.0	3.3	3.7	4.0	4.3	4.6	4.9	5.2	5.4
Dec	0.8	1.1	1.5	1.9	2.3	2.6	3.0	3.3	3.6	3.8	4.1	4.4	4.6	4.7	5.0

Table E9

Latitude= -37.5
Tilt = 27.5 H (kWh/m2)

	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5	8.0
Jan	0.9	1.4	1.9	2.4	2.8	3.3	3.7	4.2	4.7	5.1	5.6	6.0	6.5	6.9	7.4
Feb	0.9	1.4	1.9	2.4	2.9	3.4	3.9	4.4	4.9	5.4	6.0	6.5	7.0	7.6	8.1
Marc	1.0	1.4	1.9	2.5	3.0	3.6	4.2	4.9	5.6	6.2	7.0	7.4	8.0	8.8	9.2
April	1.0	1.5	2.1	2.8	3.5	4.4	5.3	6.3	6.4	7.3	8.4	8.7	9.5	10.5	11.0
May	1.0	1.7	2.5	3.5	4.7	5.0	6.3	7.6	7.4	8.6	10.1	10.1	11.2	12.6	13.1
June	1.1	1.9	3.0	4.3	5.1	5.4	6.8	8.3	8.0	9.4	11.1	11.0	12.2	13.9	14.3
July	1.0	1.8	2.8	3.9	5.3	5.2	6.6	8.0	7.7	9.0	10.6	10.6	11.7	13.3	13.7
Aug	1.0	1.6	2.2	3.0	3.9	5.0	6.0	6.8	6.8	7.8	9.1	9.2	10.1	11.3	11.8
Sept	1.0	1.5	2.0	2.5	3.1	3.8	4.6	5.3	6.1	6.9	7.5	7.8	8.5	9.4	9.9
Oct	0.9	1.4	1.9	2.4	2.9	3.4	4.0	4.5	5.1	5.6	6.2	6.8	7.4	7.9	8.4
Nov	0.9	1.4	1.9	2.4	2.8	3.3	3.8	4.2	4.7	5.2	5.7	6.1	6.6	7.1	7.5
Dec	0.9	1.4	1.9	2.3	2.8	3.3	3.7	4.2	4.6	5.1	5.5	5.9	6.3	6.8	7.2

Table E10

Latitude= -37.5
Tilt = 37.5 H (kWh/m2)

	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5	8.0
Jan	0.8	1.3	1.8	2.2	2.7	3.1	3.5	4.0	4.4	4.8	5.2	5.6	6.0	6.4	6.8
Feb	0.9	1.3	1.8	2.3	2.7	3.2	3.7	4.2	4.7	5.2	5.7	6.2	6.7	7.3	7.7
Marc	0.9	1.4	1.9	2.4	2.9	3.5	4.1	4.8	5.5	6.2	7.0	7.3	8.0	8.8	9.2
April	0.9	1.5	2.1	2.7	3.5	4.5	5.6	6.7	6.6	7.6	8.9	9.0	9.9	11.1	11.6
May	1.0	1.7	2.6	3.8	5.1	5.4	6.8	8.3	7.9	9.3	11.0	11.0	12.1	13.8	14.2
June	1.1	1.9	3.2	4.7	5.7	5.9	7.5	9.3	8.7	10.3	12.4	12.2	13.5	15.5	15.9
July	1.0	1.8	2.9	4.2	5.9	5.6	7.2	8.8	8.3	9.8	11.8	11.6	12.9	14.7	15.1
Aug	1.0	1.5	2.2	3.1	4.1	5.3	6.5	7.3	7.1	8.3	9.7	9.8	10.8	12.1	12.6
Sept	1.0	1.4	1.9	2.5	3.1	3.8	4.6	5.3	6.2	7.0	7.7	7.9	8.7	9.6	10.0
Oct	0.9	1.4	1.8	2.3	2.8	3.3	3.8	4.3	4.9	5.4	6.0	6.6	7.2	7.7	8.1
Nov	0.9	1.3	1.8	2.2	2.7	3.1	3.6	4.0	4.4	4.9	5.3	5.7	6.2	6.6	7.0
Dec	0.9	1.3	1.8	2.2	2.7	3.1	3.5	3.9	4.3	4.7	5.1	5.5	5.8	6.2	6.6

Table E11

Latitude= -37.5
Tilt = 47.5 H (kWh/m2)

	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5	8.0
Jan	0.8	1.3	1.7	2.1	2.5	2.9	3.3	3.6	4.0	4.3	4.7	5.1	5.4	5.7	6.0
Feb	0.8	1.3	1.7	2.1	2.5	3.0	3.4	3.9	4.3	4.8	5.3	5.8	6.2	6.7	7.1
Marc	0.9	1.3	1.8	2.3	2.8	3.3	3.9	4.6	5.3	6.0	6.8	7.1	7.7	8.5	8.9
April	0.9	1.4	2.0	2.7	3.5	4.5	5.6	6.8	6.7	7.7	9.1	9.1	10.1	11.3	11.8
May	1.0	1.7	2.6	3.9	5.3	5.5	7.1	8.8	8.2	9.7	11.7	11.5	12.8	14.6	15.0
June	1.0	2.0	3.3	5.0	6.0	6.2	8.0	10.0	9.2	11.0	13.3	12.9	14.4	16.7	17.1
July	1.0	1.8	3.0	4.4	6.3	5.9	7.6	9.4	8.7	10.4	12.6	12.3	13.6	15.7	16.1
Aug	1.0	1.5	2.1	3.1	4.1	5.4	6.7	7.6	7.3	8.5	10.1	10.0	11.1	12.6	13.0
Sept	0.9	1.3	1.8	2.4	2.9	3.7	4.5	5.2	6.1	7.0	7.6	7.8	8.5	9.5	9.9
Oct	0.8	1.3	1.7	2.1	2.6	3.1	3.6	4.0	4.6	5.1	5.6	6.2	6.7	7.2	7.6
Nov	0.8	1.2	1.7	2.1	2.5	2.9	3.3	3.7	4.1	4.4	4.8	5.2	5.6	5.9	6.3
Dec	0.8	1.2	1.6	2.1	2.5	2.9	3.2	3.6	3.9	4.3	4.6	4.9	5.2	5.5	5.8

Table E12

Latitude= -37.5
Tilt = 57.5 H (kWh/m2)

	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5	8.0
Jan	0.7	1.1	1.5	1.9	2.2	2.6	2.9	3.3	3.6	3.8	4.1	4.4	4.7	4.9	5.2
Feb	0.8	1.2	1.5	1.9	2.3	2.7	3.1	3.5	3.9	4.3	4.7	5.1	5.6	6.0	6.4
Marc	0.8	1.2	1.6	2.1	2.6	3.1	3.6	4.3	4.9	5.6	6.4	6.6	7.2	8.0	8.4
April	0.8	1.3	1.9	2.5	3.4	4.4	5.5	6.7	6.5	7.6	9.0	9.0	9.9	11.2	11.6
May	0.9	1.6	2.6	3.9	5.4	5.6	7.2	9.0	8.3	9.9	12.0	11.7	13.0	15.0	15.4
June	1.0	1.9	3.4	5.2	6.2	6.3	8.3	10.4	9.4	11.3	13.9	13.4	14.9	17.3	17.7
July	0.9	1.7	3.0	4.5	6.5	6.0	7.8	9.7	8.9	10.7	13.0	12.6	14.0	16.2	16.6
Aug	0.9	1.4	2.1	3.0	4.1	5.4	6.8	7.6	7.2	8.5	10.1	10.0	11.1	12.7	13.1
Sept	0.8	1.2	1.7	2.2	2.8	3.5	4.2	5.0	5.9	6.7	7.3	7.5	8.2	9.1	9.5
Oct	0.8	1.2	1.6	2.0	2.4	2.8	3.2	3.7	4.2	4.6	5.1	5.6	6.1	6.5	6.9
Nov	0.8	1.1	1.5	1.9	2.3	2.6	3.0	3.3	3.6	4.0	4.3	4.5	4.9	5.1	5.4
Dec	0.8	1.1	1.5	1.9	2.2	2.6	2.9	3.2	3.5	3.8	4.0	4.3	4.5	4.7	4.9

Table E13

Latitude= -40.0
Tilt = 30.0 H (kWh/m2)

	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5	8.0
Jan	0.9	1.4	1.9	2.3	2.8	3.3	3.7	4.2	4.6	5.1	5.5	6.0	6.4	6.9	7.3
Feb	0.9	1.4	1.9	2.4	2.9	3.3	3.9	4.4	4.9	5.5	6.0	6.6	7.1	7.6	8.2
Marc	0.9	1.4	1.9	2.5	3.0	3.7	4.3	5.0	5.7	6.4	7.2	7.5	8.3	8.7	9.5
April	1.0	1.5	2.1	2.9	3.8	4.7	5.7	5.8	6.8	7.8	8.9	9.0	10.1	10.4	11.6
May	1.0	1.8	2.7	4.0	5.4	5.5	6.9	6.6	8.0	9.4	10.9	10.8	12.3	12.5	14.0
June	1.1	2.1	3.5	5.1	6.1	6.1	7.6	7.2	8.8	10.5	12.2	12.0	13.7	13.8	15.6
July	1.1	1.9	3.1	4.6	5.8	5.8	7.3	6.9	8.4	10.0	11.5	11.4	13.0	13.2	14.9
Aug	1.0	1.6	2.3	3.2	4.3	5.4	6.1	6.1	7.2	8.4	9.6	9.7	10.9	11.2	12.5
Sept	1.0	1.5	2.0	2.6	3.2	3.9	4.7	5.5	6.4	6.9	7.8	8.1	8.9	9.3	10.2
Oct	0.9	1.4	1.9	2.4	2.9	3.4	4.0	4.5	5.1	5.7	6.3	6.9	7.5	7.9	8.5
Nov	0.9	1.4	1.9	2.3	2.8	3.3	3.7	4.2	4.7	5.2	5.6	6.1	6.6	7.1	7.5
Dec	0.9	1.4	1.9	2.3	2.8	3.2	3.7	4.1	4.6	5.0	5.4	5.9	6.3	6.7	7.2

Table E14

Latitude= -40.0
Tilt = 40.0 H (kWh/m2)

	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5	8.0
Jan	1.3	1.8	2.2	2.6	3.1	3.5	3.9	4.3	4.7	5.2	5.6	6.0	6.4	6.8	7.2
Feb	1.5	1.8	2.2	2.7	3.2	3.7	4.2	4.7	5.2	5.7	6.3	6.8	7.2	7.8	8.2
Marc	1.8	1.8	2.4	2.9	3.6	4.2	4.9	5.6	6.4	7.2	7.5	8.3	8.6	9.4	9.9
April	1.5	2.1	2.9	3.9	4.8	5.9	5.9	7.0	8.2	9.3	9.4	10.6	10.9	12.1	12.6
May	1.8	2.8	4.2	6.0	5.9	7.5	7.0	8.6	10.2	11.9	11.7	13.4	13.5	15.3	15.8
June	2.2	3.8	5.7	6.8	6.6	8.5	7.7	9.6	11.6	13.6	13.2	15.2	15.2	17.4	17.8
July	2.0	3.4	5.0	6.4	6.3	8.0	7.4	9.1	11.0	12.8	12.5	14.4	14.4	16.4	16.8
Aug	1.5	2.3	3.3	4.5	5.7	6.5	6.3	7.6	9.0	10.3	10.3	11.7	11.9	13.3	13.8
Sept	1.4	1.9	2.5	3.2	3.9	4.7	5.5	6.5	7.0	7.9	8.2	9.1	9.4	10.4	10.8
Oct	1.4	1.8	2.3	2.8	3.2	3.8	4.4	4.9	5.5	6.1	6.7	7.2	7.6	8.3	8.7
Nov	1.3	1.8	2.2	2.6	3.1	3.5	4.0	4.4	4.8	5.3	5.7	6.1	6.6	7.0	7.4
Dec	1.3	1.7	2.2	2.6	3.0	3.5	3.9	4.3	4.7	5.0	5.4	5.8	6.2	6.6	6.9

Table E15

Latitude= -40.0
Tilt = 50.0 H (kWh/m2)

	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5	8.0
Jan	0.8	1.2	1.6	2.0	2.4	2.8	3.2	3.6	3.9	4.3	4.7	5.0	5.4	5.7	6.0
Feb	0.8	1.2	1.7	2.1	2.5	2.9	3.4	3.9	4.3	4.8	5.3	5.8	6.3	6.7	7.2
Marc	0.8	1.2	1.7	2.2	2.8	3.4	4.0	4.7	5.4	6.2	7.0	7.2	8.0	8.3	9.1
April	0.8	1.4	2.0	2.8	3.8	4.9	6.0	5.9	7.1	8.3	9.5	9.5	10.8	11.0	12.3
May	1.0	1.8	2.9	4.4	6.3	6.2	7.8	7.2	9.0	10.8	12.6	12.3	14.1	14.1	16.1
June	1.1	2.3	4.0	6.1	7.3	7.0	9.0	8.1	10.2	12.4	14.6	14.0	16.3	16.1	18.6
July	1.0	2.0	3.5	5.3	6.8	6.6	8.5	7.7	9.6	11.6	13.6	13.2	15.3	15.2	17.4
Aug	0.9	1.5	2.3	3.3	4.6	5.9	6.7	6.4	7.8	9.2	10.7	10.6	12.1	12.2	13.8
Sept	0.9	1.3	1.8	2.4	3.1	3.8	4.5	5.4	6.4	6.9	7.9	8.0	9.0	9.3	10.3
Oct	0.8	1.3	1.7	2.1	2.6	3.0	3.5	4.1	4.6	5.1	5.7	6.3	6.8	7.1	7.7
Nov	0.8	1.2	1.6	2.0	2.4	2.8	3.2	3.6	4.0	4.4	4.8	5.2	5.6	5.9	6.3
Dec	0.8	1.2	1.6	2.0	2.4	2.8	3.2	3.5	3.9	4.2	4.5	4.9	5.2	5.5	5.8

Table E16

Latitude= -40.0
Tilt = 60.0 H (kWh/m2)

	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5	8.0
Jan	0.6	1.1	1.5	1.8	2.2	2.5	2.9	3.2	3.5	3.8	4.1	4.4	4.6	4.9	5.1
Feb	0.8	1.1	1.5	1.9	2.3	2.7	3.1	3.5	3.9	4.3	4.7	5.2	5.6	6.0	6.4
Marc	0.8	1.1	1.6	2.1	2.5	3.2	3.7	4.4	5.1	5.8	6.6	6.8	7.5	7.8	8.6
April	0.8	1.3	1.9	2.7	3.7	4.8	6.0	5.7	6.9	8.2	9.4	9.4	10.7	10.8	12.2
May	0.9	1.7	2.9	4.5	6.5	6.2	8.0	7.3	9.1	11.0	12.9	12.5	14.4	14.4	16.5
June	1.0	2.3	4.1	6.3	7.6	7.2	9.3	8.2	10.5	12.8	15.2	14.5	16.9	16.6	19.3
July	1.0	1.9	3.6	5.5	7.1	6.7	8.7	7.8	9.8	11.9	14.1	13.5	15.7	15.5	17.9
Aug	0.9	1.4	2.2	3.3	4.6	5.9	6.7	6.3	7.7	9.2	10.8	10.6	12.1	12.2	13.8
Sept	0.8	1.2	1.7	2.2	2.9	3.6	4.3	5.2	6.2	6.6	7.6	7.7	8.6	8.8	9.8
Oct	0.8	1.1	1.5	1.9	2.3	2.8	3.2	3.7	4.2	4.7	5.2	5.7	6.1	6.5	7.0
Nov	0.7	1.1	1.5	1.9	2.2	2.6	2.9	3.2	3.6	3.9	4.2	4.5	4.8	5.1	5.4
Dec	0.7	1.1	1.5	1.8	2.2	2.5	2.8	3.1	3.4	3.7	4.0	4.2	4.5	4.7	4.9

Table E17

Latitude= -42.5
Tilt = 32.5
H (kWh/m2)

	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5	8.0
Jan	0.9	1.4	1.8	2.3	2.8	3.2	3.7	4.1	4.6	5.1	5.5	6.0	6.4	6.9	7.3
Feb	0.9	1.4	1.9	2.3	2.8	3.3	3.9	4.4	4.9	5.5	6.0	6.6	7.2	7.6	8.2
Marc	0.9	1.4	1.9	2.5	3.1	3.7	4.4	5.1	5.9	6.7	6.9	7.7	8.5	8.9	9.7
April	0.9	1.5	2.2	3.0	4.0	5.0	6.3	6.1	7.3	8.4	8.3	9.5	10.7	10.9	12.2
May	1.1	1.9	3.1	4.5	4.7	6.0	7.9	7.2	9.0	10.5	10.0	11.7	13.3	13.4	15.2
June	1.3	2.4	4.1	5.1	5.2	6.8	9.0	8.0	10.1	11.9	11.1	13.1	15.1	15.1	17.2
July	1.1	2.2	3.6	4.8	5.0	6.4	8.5	7.6	9.6	11.2	10.6	12.4	14.2	14.3	16.3
Aug	1.0	1.7	2.5	3.5	4.6	6.0	6.9	6.5	7.9	9.2	9.0	10.3	11.7	11.9	13.3
Sept	1.0	1.5	2.0	2.6	3.3	4.1	4.8	5.8	6.7	7.3	7.4	8.3	9.3	9.6	10.6
Oct	0.9	1.4	1.9	2.4	2.9	3.4	4.0	4.6	5.2	5.8	6.4	7.0	7.6	8.0	8.7
Nov	0.9	1.4	1.8	2.3	2.8	3.2	3.7	4.2	4.7	5.1	5.6	6.1	6.6	7.1	7.6
Dec	0.9	1.4	1.8	2.3	2.8	3.2	3.7	4.1	4.5	5.0	5.4	5.9	6.3	6.7	7.1

Table E18

Latitude= -42.5
Tilt = 42.5
H (kWh/m2)

	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5	8.0
Jan	0.8	1.3	1.7	2.2	2.6	3.0	3.4	3.9	4.3	4.7	5.1	5.5	5.9	6.4	6.8
Feb	0.9	1.3	1.8	2.2	2.7	3.2	3.7	4.2	4.7	5.2	5.7	6.3	6.9	7.3	7.9
Marc	0.9	1.3	1.8	2.4	3.0	3.6	4.3	5.0	5.9	6.7	6.8	7.7	8.5	8.8	9.7
April	0.9	1.5	2.2	3.0	4.1	5.1	6.6	6.2	7.6	8.8	8.6	9.9	11.2	11.4	12.8
May	1.1	2.0	3.3	4.9	5.0	6.5	8.6	7.7	9.7	11.4	10.7	12.6	14.5	14.5	16.6
June	1.3	2.6	4.5	5.6	5.7	7.4	10.0	8.6	11.2	13.2	12.1	14.4	16.8	16.6	19.1
July	1.1	2.3	3.9	5.3	5.4	7.0	9.3	8.2	10.5	12.3	11.4	13.5	15.7	15.6	17.9
Aug	1.0	1.6	2.5	3.6	4.9	6.4	7.3	6.8	8.4	9.8	9.4	10.9	12.4	12.6	14.2
Sept	0.9	1.4	1.9	2.5	3.3	4.1	4.9	5.8	6.9	7.4	7.4	8.4	9.4	9.7	10.8
Oct	0.9	1.3	1.8	2.3	2.7	3.3	3.8	4.4	5.0	5.6	6.2	6.8	7.3	7.7	8.4
Nov	0.9	1.3	1.7	2.2	2.6	3.0	3.5	3.9	4.4	4.8	5.2	5.7	6.1	6.6	7.0
Dec	0.9	1.3	1.7	2.2	2.6	3.0	3.4	3.8	4.2	4.6	5.0	5.4	5.8	6.1	6.5

Table E19

Latitude= -42.5
Tilt = 52.5 H (kWh/m2)

	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5	8.0
Jan	0.8	1.2	1.6	2.0	2.4	2.8	3.2	3.5	3.9	4.3	4.6	5.0	5.3	5.7	6.0
Feb	0.8	1.2	1.6	2.1	2.5	2.9	3.4	3.9	4.3	4.8	5.3	5.8	6.3	6.7	7.2
Marc	0.8	1.2	1.7	2.2	2.8	3.4	4.2	4.8	5.7	6.5	6.6	7.4	8.2	8.5	9.4
April	0.8	1.4	2.1	3.0	4.1	5.2	6.7	6.3	7.7	9.0	8.6	10.0	11.4	11.5	13.0
May	1.0	2.0	3.4	5.1	5.2	6.8	9.1	8.0	10.2	12.0	11.1	13.2	15.3	15.2	17.5
June	1.3	2.7	4.8	6.0	5.9	7.8	10.7	9.1	11.9	14.1	12.7	15.3	17.9	17.6	20.4
July	1.1	2.3	4.1	5.6	5.6	7.3	10.0	8.5	11.1	13.1	11.9	14.3	16.7	16.5	19.0
Aug	0.9	1.6	2.5	3.6	5.0	6.7	7.6	6.9	8.6	10.1	9.6	11.2	12.8	12.9	14.7
Sept	0.9	1.3	1.8	2.4	3.1	4.0	4.7	5.8	6.8	7.3	7.3	8.3	9.3	9.6	10.6
Oct	0.8	1.2	1.6	2.1	2.6	3.0	3.5	4.1	4.6	5.2	5.8	6.4	6.9	7.2	7.9
Nov	0.8	1.2	1.6	2.0	2.4	2.8	3.2	3.6	4.0	4.4	4.8	5.1	5.5	5.9	6.3
Dec	0.8	1.2	1.6	2.0	2.4	2.8	3.1	3.5	3.8	4.2	4.5	4.8	5.1	5.4	5.8

Table E20

Latitude= -42.5
Tilt = 62.5 H (kWh/m2)

	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5	8.0
Jan	0.6	1.1	1.4	1.8	2.2	2.5	2.8	3.1	3.4	3.7	4.0	4.3	4.6	4.9	5.1
Feb	0.7	1.1	1.5	1.9	2.2	2.6	3.1	3.5	3.9	4.3	4.7	5.2	5.7	6.0	6.5
Marc	0.7	1.1	1.6	2.0	2.6	3.2	3.9	4.5	5.3	6.1	6.1	6.9	7.7	8.0	8.8
April	0.8	1.3	2.0	2.8	4.0	5.1	6.7	6.1	7.6	8.8	8.4	9.8	11.2	11.3	12.8
May	1.0	1.9	3.4	5.2	5.2	6.9	9.3	8.0	10.4	12.3	11.2	13.4	15.6	15.4	17.8
June	1.2	2.7	5.0	6.2	6.0	8.1	11.2	9.2	12.2	14.6	13.0	15.8	18.6	18.1	21.2
July	1.0	2.3	4.2	5.7	5.7	7.5	10.3	8.7	11.3	13.5	12.2	14.7	17.2	16.9	19.6
Aug	0.9	1.5	2.4	3.6	4.9	6.7	7.7	6.8	8.6	10.1	9.5	11.2	12.9	12.9	14.7
Sept	0.8	1.2	1.7	2.2	3.0	3.8	4.5	5.5	6.6	7.0	6.9	7.9	8.9	9.1	10.2
Oct	0.7	1.1	1.5	1.9	2.3	2.8	3.2	3.7	4.2	4.7	5.2	5.8	6.2	6.6	7.1
Nov	0.7	1.1	1.4	1.8	2.2	2.5	2.9	3.2	3.5	3.9	4.2	4.5	4.8	5.1	5.4
Dec	0.7	1.1	1.4	1.8	2.1	2.5	2.8	3.1	3.4	3.7	3.9	4.2	4.4	4.6	4.9

Table E21

Latitude= -45.0
Tilt = 35.0 H (kWh/m2)

	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5	8.0
Jan	0.9	1.4	1.8	2.3	2.7	3.2	3.7	4.1	4.6	5.0	5.5	6.0	6.4	6.9	7.4
Feb	0.9	1.4	1.9	2.3	2.8	3.3	3.9	4.4	5.0	5.5	6.1	6.7	7.4	7.7	8.3
Marc	0.9	1.4	1.9	2.5	3.1	3.8	4.5	5.3	6.1	7.0	7.2	8.1	8.9	9.2	10.0
April	0.9	1.6	2.3	3.3	4.3	5.5	5.4	6.6	7.7	9.1	8.9	10.3	11.6	11.5	12.9
May	1.1	2.2	3.7	5.4	5.2	7.1	6.4	8.1	9.8	11.9	11.1	13.1	15.1	14.6	16.6
June	1.5	3.0	4.2	6.3	5.9	8.2	7.1	9.2	11.2	13.8	12.5	15.1	17.6	16.6	19.2
July	1.3	2.5	4.4	5.9	5.6	7.7	6.8	8.7	10.5	12.9	11.8	14.1	16.4	15.6	17.9
Aug	1.0	1.7	2.7	3.9	5.2	6.1	5.8	7.1	8.5	10.1	9.7	11.3	12.9	12.6	14.3
Sept	1.0	1.5	2.0	2.7	3.5	4.3	5.2	6.1	6.7	7.7	7.8	8.8	9.9	10.0	11.0
Oct	0.9	1.4	1.9	2.4	2.9	3.4	4.0	4.6	5.2	5.9	6.6	7.3	7.8	8.1	8.8
Nov	0.9	1.4	1.8	2.3	2.8	3.2	3.7	4.2	4.6	5.1	5.6	6.1	6.6	7.1	7.6
Dec	0.9	1.4	1.8	2.3	2.7	3.2	3.6	4.1	4.5	4.9	5.4	5.8	6.3	6.7	7.1

Table E22

Latitude= -45.0
Tilt = 45.0 H (kWh/m2)

	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5	8.0
Jan	0.8	1.3	1.7	2.1	2.6	3.0	3.4	3.8	4.3	4.7	5.1	5.5	5.9	6.4	6.8
Feb	0.9	1.3	1.7	2.2	2.7	3.1	3.7	4.2	4.7	5.2	5.8	6.4	7.0	7.3	7.9
Marc	0.9	1.4	1.8	2.4	3.0	3.7	4.4	5.2	6.1	7.0	7.1	8.0	8.9	9.1	10.0
April	0.9	1.5	2.3	3.3	4.4	5.8	5.5	6.8	8.0	9.6	9.2	10.7	12.2	12.0	13.5
May	1.1	2.3	3.9	5.9	5.6	7.7	6.8	8.7	10.6	13.0	11.9	14.2	16.5	15.7	18.1
June	1.5	3.3	4.6	7.0	6.4	9.0	7.6	10.0	12.3	15.4	13.7	16.7	19.6	18.3	21.3
July	1.3	2.7	4.8	6.5	6.0	8.4	7.2	9.4	11.5	14.2	12.8	15.5	18.1	17.1	19.7
Aug	1.0	1.7	2.8	4.0	5.6	6.5	6.0	7.5	9.0	10.9	10.2	12.0	13.8	13.4	15.2
Sept	0.9	1.4	2.0	2.6	3.4	4.3	5.2	6.2	6.7	7.9	7.8	8.9	10.1	10.1	11.2
Oct	0.9	1.3	1.8	2.2	2.7	3.3	3.8	4.4	5.0	5.7	6.3	7.0	7.6	7.8	8.5
Nov	0.9	1.3	1.7	2.1	2.6	3.0	3.4	3.9	4.3	4.8	5.2	5.7	6.1	6.6	7.1
Dec	0.9	1.3	1.7	2.1	2.5	3.0	3.4	3.8	4.2	4.6	5.0	5.4	5.7	6.1	6.5

Table E23

Latitude= -45.0
Tilt = 55.0 H (kWh/m2)

	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5	8.0
Jan	0.8	1.2	1.6	2.0	2.3	2.7	3.1	3.5	3.9	4.2	4.6	5.0	5.3	5.7	6.0
Feb	0.8	1.2	1.6	2.0	2.5	2.9	3.4	3.8	4.3	4.8	5.4	5.9	6.5	6.8	7.3
Marc	0.8	1.3	1.7	2.2	2.8	3.5	4.2	5.0	5.8	6.8	6.8	7.7	8.7	8.8	9.7
April	0.8	1.4	2.3	3.3	4.4	5.9	5.5	6.8	8.1	9.8	9.3	10.9	12.5	12.2	13.8
May	1.1	2.3	4.1	6.3	5.8	8.1	7.0	9.1	11.1	13.7	12.4	14.9	17.5	16.5	19.1
June	1.5	3.4	4.8	7.5	6.7	9.7	7.9	10.6	13.1	16.5	14.5	17.8	21.0	19.4	22.8
July	1.3	2.8	5.1	6.9	6.3	8.9	7.5	9.9	12.1	15.2	13.5	16.4	19.3	18.0	21.0
Aug	1.0	1.6	2.8	4.1	5.7	6.7	6.0	7.7	9.2	11.3	10.4	12.4	14.3	13.8	15.7
Sept	0.9	1.3	1.9	2.5	3.3	4.2	5.1	6.1	6.6	7.8	7.7	8.8	10.0	9.9	11.1
Oct	0.8	1.2	1.6	2.1	2.5	3.0	3.5	4.1	4.7	5.3	5.9	6.6	7.1	7.3	8.0
Nov	0.8	1.2	1.6	2.0	2.4	2.8	3.2	3.5	3.9	4.3	4.7	5.1	5.5	5.9	6.3
Dec	0.8	1.2	1.6	1.9	2.3	2.7	3.1	3.4	3.8	4.1	4.4	4.8	5.1	5.4	5.7

Table E24

Latitude= -45.0
Tilt = 65.0 H (kWh/m2)

	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5	8.0
Jan	0.6	1.1	1.4	1.8	2.1	2.4	2.8	3.1	3.4	3.7	4.0	4.3	4.6	4.9	5.1
Feb	0.7	1.1	1.4	1.8	2.2	2.6	3.0	3.4	3.9	4.3	4.8	5.3	5.8	6.0	6.5
Marc	0.7	1.1	1.6	2.1	2.6	3.3	3.9	4.7	5.5	6.4	6.4	7.2	8.1	8.2	9.1
April	0.7	1.3	2.1	3.2	4.3	5.8	5.3	6.7	8.0	9.7	9.1	10.7	12.4	12.0	13.6
May	1.0	2.3	4.2	6.4	5.8	8.3	7.0	9.2	11.3	14.1	12.5	15.2	17.9	16.7	19.5
June	1.5	3.5	5.0	7.8	6.9	10.0	8.0	10.9	13.5	17.1	14.9	18.3	21.8	20.0	23.5
July	1.2	2.8	5.2	7.1	6.4	9.1	7.5	10.0	12.4	15.6	13.8	16.8	19.9	18.4	21.6
Aug	0.9	1.6	2.7	4.1	5.8	6.7	5.9	7.6	9.2	11.3	10.4	12.4	14.4	13.7	15.8
Sept	0.8	1.2	1.7	2.3	3.1	4.0	4.9	5.8	6.3	7.5	7.3	8.4	9.6	9.5	10.6
Oct	0.7	1.1	1.5	1.9	2.3	2.7	3.2	3.7	4.3	4.8	5.4	6.0	6.4	6.6	7.2
Nov	0.7	1.1	1.4	1.8	2.1	2.5	2.8	3.1	3.5	3.8	4.1	4.5	4.8	5.1	5.4
Dec	0.7	1.0	1.4	1.7	2.1	2.4	2.7	3.0	3.3	3.6	3.8	4.1	4.4	4.6	4.8

Appendix F: Combination of Array Rating and Battery Storage Capacity (Wp) Required for Specified Conditions

Table F1

Average Daily Radiation (H, kWh/m2) for Month

AC/BC = 0.01
R = 0.33
DOD = 0.30

Average Daily Demand (kWh)		1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5	8.0	8.5
	0.1	133.6	94.1	73.8	61.3	52.7	46.5	41.8	38.1	35.0	32.5	30.4	28.6	27.0	25.6	24.4	23.3
		0.5	0.4	0.4	0.4	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
	0.2	267.3	188.2	147.6	122.5	105.5	93.1	83.6	76.2	70.1	65.0	60.8	57.2	54.0	51.2	48.8	46.6
		1.0	0.8	0.8	0.7	0.7	0.6	0.6	0.6	0.6	0.6	0.6	0.5	0.5	0.5	0.5	0.5
	0.3	400.9	282.4	221.3	183.8	158.2	139.6	125.4	114.2	105.1	97.6	91.2	85.7	81.0	76.8	73.2	69.9
		1.4	1.2	1.1	1.1	1.0	1.0	0.9	0.9	0.9	0.9	0.8	0.8	0.8	0.8	0.8	0.8
	0.4	534.5	376.5	295.1	245.1	211.0	186.2	167.3	152.3	140.2	130.1	121.6	114.3	108.0	102.5	97.6	93.2
		1.9	1.7	1.5	1.4	1.3	1.3	1.2	1.2	1.2	1.1	1.1	1.1	1.1	1.1	1.0	1.0
Average Daily Demand (kWh)	0.5	668.1	470.6	368.9	306.3	263.7	232.7	209.1	190.4	175.2	162.6	152.0	142.9	135.0	128.1	121.9	116.5
		2.4	2.1	1.9	1.8	1.7	1.6	1.5	1.5	1.5	1.4	1.4	1.4	1.3	1.3	1.3	1.3
	0.6	801.8	564.7	442.7	367.6	316.5	279.3	250.9	228.5	210.2	195.1	182.4	171.5	162.0	153.7	146.3	139.8
		2.9	2.5	2.3	2.1	2.0	1.9	1.9	1.8	1.7	1.7	1.7	1.6	1.6	1.6	1.6	1.5
	0.7	935.4	658.9	516.5	428.9	369.2	325.8	292.7	266.5	245.3	227.6	212.8	200.0	189.0	179.3	170.7	163.1
		3.3	2.9	2.7	2.5	2.3	2.2	2.2	2.1	2.0	2.0	1.9	1.9	1.9	1.8	1.8	1.8
	0.8	1069.0	753.0	590.2	490.2	422.0	372.4	334.5	304.6	280.3	260.2	243.2	228.6	216.0	204.9	195.1	186.4
		3.8	3.3	3.0	2.8	2.7	2.6	2.5	2.4	2.3	2.3	2.2	2.2	2.1	2.1	2.1	2.1
	0.9	1202.7	847.1	664.0	551.4	474.7	418.9	376.3	342.7	315.4	292.7	273.6	257.2	243.0	230.5	219.5	209.7
		4.3	3.7	3.4	3.2	3.0	2.9	2.8	2.7	2.6	2.6	2.5	2.5	2.4	2.4	2.3	2.3
	1.0	1336.3	941.2	737.8	612.7	527.5	465.5	418.1	380.8	350.4	325.2	304.0	285.8	270.0	256.1	243.9	233.0
		4.8	4.2	3.8	3.5	3.4	3.2	3.1	3.0	2.9	2.8	2.8	2.7	2.7	2.6	2.6	2.6

Table F2

Average Daily Radiation (H, kWh/m2) for Month

AC/BC = 0.01
R = 0.33
DOD = 0.50

Average Daily Demand (kWh)	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5	8.0	8.5
0.1	126.0	87.9	68.4	56.5	48.4	42.5	38.0	34.5	31.6	29.3	27.3	25.6	24.1	22.8	21.7	20.7
	0.3	0.3	0.3	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
0.2	252.1	175.9	136.8	112.9	96.7	85.0	76.0	69.0	63.3	58.6	54.6	51.2	48.3	45.7	43.4	41.4
	0.7	0.6	0.5	0.5	0.5	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.3
0.3	378.1	263.8	205.3	169.4	145.1	127.5	114.1	103.5	94.9	87.9	81.9	76.8	72.4	68.5	65.1	62.1
	1.0	0.9	0.8	0.7	0.7	0.7	0.6	0.6	0.6	0.6	0.6	0.6	0.5	0.5	0.5	0.5
0.4	504.2	351.7	273.7	225.9	193.5	170.0	152.1	138.0	126.6	117.2	109.2	102.4	96.5	91.4	86.8	82.8
	1.4	1.2	1.1	1.0	0.9	0.9	0.9	0.8	0.8	0.8	0.8	0.7	0.7	0.7	0.7	0.7
0.5	630.2	439.7	342.1	282.4	241.9	212.5	190.1	172.5	158.2	146.4	136.5	128.0	120.7	114.2	108.5	103.5
	1.7	1.5	1.3	1.2	1.2	1.1	1.1	1.0	1.0	1.0	1.0	0.9	0.9	0.9	0.9	0.9
0.6	756.3	527.6	410.5	338.8	290.2	255.0	228.1	207.0	189.9	175.7	163.8	153.6	144.8	137.1	130.3	124.2
	2.1	1.8	1.6	1.5	1.4	1.3	1.3	1.2	1.2	1.2	1.1	1.1	1.1	1.1	1.1	1.0
0.7	882.3	615.5	478.9	395.3	338.6	297.5	266.2	241.5	221.5	205.0	191.1	179.2	168.9	159.9	152.0	144.9
	2.4	2.1	1.9	1.7	1.6	1.6	1.5	1.5	1.4	1.4	1.3	1.3	1.3	1.3	1.2	1.2
0.8	1008.4	703.5	547.4	451.8	387.0	340.0	304.2	276.0	253.2	234.3	218.4	204.8	193.1	182.8	173.7	165.6
	2.8	2.4	2.2	2.0	1.9	1.8	1.7	1.7	1.6	1.6	1.5	1.5	1.5	1.4	1.4	1.4
0.9	1134.4	791.4	615.8	508.3	435.4	382.5	342.2	310.5	284.8	263.6	245.7	230.4	217.2	205.6	195.4	186.3
	3.1	2.7	2.4	2.2	2.1	2.0	1.9	1.9	1.8	1.8	1.7	1.7	1.6	1.6	1.6	1.6
1.0	1260.5	879.4	684.2	564.7	483.7	425.0	380.2	345.0	316.5	292.9	273.0	256.0	241.3	228.5	217.1	207.0
	3.5	3.0	2.7	2.5	2.4	2.2	2.1	2.1	2.0	2.0	1.9	1.9	1.8	1.8	1.8	1.7

Table F3

Average Daily Radiation (H, kWh/m2) for Month

AC/BC = 0.01
R = 0.45
DOD = 0.30

Average Daily Demand (kWh)	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5	8.0	8.5
0.1	145.8	104.0	82.4	68.9	59.8	53.0	47.9	43.8	40.5	37.7	35.4	33.3	31.6	30.0	28.7	27.5
	0.7	0.6	0.6	0.6	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.4	0.4	0.4	0.4	0.4
0.2	291.5	208.1	164.7	137.9	119.5	106.1	95.8	87.6	80.9	75.4	70.7	66.7	63.2	60.1	57.4	54.9
	1.4	1.3	1.2	1.1	1.1	1.0	1.0	1.0	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.8
0.3	437.3	312.1	247.1	206.8	179.3	159.1	143.7	131.4	121.4	113.1	106.1	100.0	94.8	90.1	86.0	82.4
	2.2	1.9	1.8	1.7	1.6	1.5	1.5	1.4	1.4	1.4	1.4	1.3	1.3	1.3	1.3	1.3
0.4	583.1	416.1	329.5	275.8	239.0	212.1	191.5	175.2	161.9	150.8	141.4	133.3	126.3	120.2	114.7	109.9
	2.9	2.6	2.4	2.2	2.1	2.0	2.0	1.9	1.9	1.8	1.8	1.8	1.8	1.7	1.7	1.7
0.5	728.8	520.2	411.8	344.7	298.8	265.2	239.4	219.0	202.3	188.5	176.8	166.7	157.9	150.2	143.4	137.3
	3.6	3.2	2.9	2.8	2.6	2.5	2.5	2.4	2.3	2.3	2.3	2.2	2.2	2.2	2.1	2.1
0.6	874.6	624.2	494.2	413.7	358.5	318.2	287.3	262.8	242.8	226.2	212.1	200.0	189.5	180.3	172.1	164.8
	4.3	3.8	3.5	3.3	3.2	3.1	3.0	2.9	2.8	2.8	2.7	2.7	2.6	2.6	2.6	2.5
0.7	1020.4	728.3	576.5	482.6	418.3	371.2	335.2	306.6	283.3	263.9	247.5	233.4	221.1	210.3	200.8	192.2
	5.1	4.5	4.1	3.9	3.7	3.6	3.5	3.4	3.3	3.2	3.2	3.1	3.1	3.0	3.0	3.0
0.8	1166.1	832.3	658.9	551.6	478.1	424.3	383.1	350.4	323.7	301.6	282.8	266.7	252.7	240.4	229.5	219.7
	5.8	5.1	4.7	4.4	4.2	4.1	3.9	3.8	3.8	3.7	3.6	3.6	3.5	3.5	3.4	3.4
0.9	1311.9	936.3	741.3	620.5	537.8	477.3	431.0	394.2	364.2	339.3	318.2	300.0	284.3	270.4	258.1	247.2
	6.5	5.7	5.3	5.0	4.8	4.6	4.4	4.3	4.2	4.1	4.1	4.0	3.9	3.9	3.8	3.8
1.0	1457.7	1040.4	823.6	689.5	597.6	530.4	478.8	438.0	404.7	377.0	353.5	333.4	315.8	300.5	286.8	274.6
	7.2	6.4	5.9	5.5	5.3	5.1	4.9	4.8	4.7	4.6	4.5	4.4	4.4	4.3	4.3	4.2

Table F4

Average Daily Radiation (H, kWh/m2) for Month

AC/BC = 0.01
R = 0.45
DOD = 0.50

Average Daily Demand (kWh)

	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5	8.0	8.5
0.1	135.5	95.6	75.1	62.4	53.8	47.5	42.7	38.9	35.9	33.3	31.1	29.3	27.7	26.3	25.0	23.9
	0.5	0.4	0.4	0.4	0.4	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
0.2	270.9	191.2	150.1	124.8	107.6	95.0	85.5	77.9	71.7	66.6	62.3	58.6	55.4	52.6	50.1	47.8
	1.0	0.9	0.8	0.8	0.7	0.7	0.7	0.7	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6
0.3	406.4	286.8	225.2	187.3	161.4	142.6	128.2	116.8	107.6	99.9	93.4	87.9	83.1	78.8	75.1	71.8
	1.5	1.3	1.2	1.1	1.1	1.0	1.0	1.0	1.0	0.9	0.9	0.9	0.9	0.9	0.9	0.8
0.4	541.8	382.5	300.3	249.7	215.2	190.1	170.9	155.7	143.4	133.2	124.6	117.2	110.7	105.1	100.1	95.7
	2.1	1.8	1.6	1.5	1.5	1.4	1.3	1.3	1.3	1.2	1.2	1.2	1.2	1.2	1.1	1.1
0.5	677.3	478.1	375.3	312.1	269.0	237.6	213.6	194.7	179.3	166.5	155.7	146.4	138.4	131.4	125.2	119.6
	2.6	2.2	2.0	1.9	1.8	1.7	1.7	1.6	1.6	1.6	1.5	1.5	1.5	1.4	1.4	1.4
0.6	812.7	573.7	450.4	374.5	322.8	285.1	256.4	233.6	215.1	199.8	186.8	175.7	166.1	157.7	150.2	143.5
	3.1	2.7	2.5	2.3	2.2	2.1	2.0	2.0	1.9	1.9	1.8	1.8	1.8	1.7	1.7	1.7
0.7	948.2	669.3	525.5	437.0	376.6	332.6	299.1	272.5	251.0	233.1	218.0	205.0	193.8	183.9	175.2	167.5
	3.6	3.1	2.9	2.7	2.5	2.4	2.4	2.3	2.2	2.2	2.1	2.1	2.0	2.0	2.0	2.0
0.8	1083.6	764.9	600.5	499.4	430.4	380.2	341.8	311.5	286.8	266.4	249.1	234.3	221.5	210.2	200.3	191.4
	4.1	3.6	3.3	3.1	2.9	2.8	2.7	2.6	2.5	2.5	2.4	2.4	2.3	2.3	2.3	2.2
0.9	1219.1	860.5	675.6	561.8	484.2	427.7	384.5	350.4	322.7	299.7	280.3	263.6	249.2	236.5	225.3	215.3
	4.6	4.0	3.7	3.4	3.3	3.1	3.0	2.9	2.9	2.8	2.7	2.7	2.6	2.6	2.6	2.5
1.0	1354.5	956.1	750.7	624.2	538.0	475.2	427.3	389.3	358.5	333.0	311.4	292.9	276.9	262.8	250.3	239.2
	5.1	4.5	4.1	3.8	3.6	3.5	3.4	3.3	3.2	3.1	3.0	3.0	2.9	2.9	2.8	2.8

Table F5

Average Daily Radiation (H, kWh/m2) for Month

AC/BC = 0.02
R = 0.33
DOD = 0.30

Average Daily Demand (kWh)

	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5	8.0	8.5
0.1	123.8	86.1	66.8	55.0	47.1	41.3	36.9	33.4	30.6	28.3	26.4	24.7	23.3	22.0	20.9	19.9
	0.6	0.5	0.5	0.4	0.4	0.4	0.4	0.4	0.4	0.3	0.3	0.3	0.3	0.3	0.3	0.3
0.2	247.6	172.2	133.6	110.1	94.1	82.6	73.8	66.9	61.3	56.6	52.7	49.4	46.5	44.0	41.8	39.8
	1.2	1.1	1.0	0.9	0.8	0.8	0.8	0.7	0.7	0.7	0.7	0.7	0.6	0.6	0.6	0.6
0.3	371.3	258.2	200.4	165.1	141.2	123.8	110.7	100.3	91.9	85.0	79.1	74.1	69.8	66.0	62.7	59.8
	1.9	1.6	1.4	1.3	1.2	1.2	1.1	1.1	1.1	1.0	1.0	1.0	1.0	0.9	0.9	0.9
0.4	495.1	344.3	267.3	220.2	188.2	165.1	147.6	133.7	122.5	113.3	105.5	98.8	93.1	88.1	83.6	79.7
	2.5	2.1	1.9	1.8	1.7	1.6	1.5	1.5	1.4	1.4	1.3	1.3	1.3	1.3	1.2	1.2
0.5	618.9	430.4	334.1	275.2	235.3	206.4	184.4	167.2	153.2	141.6	131.9	123.6	116.4	110.1	104.5	99.6
	3.1	2.6	2.4	2.2	2.1	2.0	1.9	1.8	1.8	1.7	1.7	1.6	1.6	1.6	1.5	1.5
0.6	742.7	516.5	400.9	330.2	282.4	247.7	221.3	200.6	183.8	169.9	158.2	148.3	139.6	132.1	125.4	119.5
	3.7	3.2	2.9	2.7	2.5	2.4	2.3	2.2	2.1	2.1	2.0	2.0	1.9	1.9	1.9	1.8
0.7	866.5	602.6	467.7	385.3	329.4	289.0	258.2	234.0	214.4	198.2	184.6	173.0	162.9	154.1	146.4	139.4
	4.3	3.7	3.3	3.1	2.9	2.8	2.7	2.6	2.5	2.4	2.3	2.3	2.2	2.2	2.2	2.1
0.8	990.2	688.7	534.5	440.3	376.5	330.3	295.1	267.5	245.1	226.6	211.0	197.7	186.2	176.1	167.3	159.4
	4.9	4.2	3.8	3.5	3.3	3.2	3.0	2.9	2.8	2.8	2.7	2.6	2.6	2.5	2.5	2.4
0.9	1114.0	774.7	601.3	495.4	423.6	371.5	332.0	300.9	275.7	254.9	237.4	222.4	209.5	198.1	188.2	179.3
	5.6	4.8	4.3	4.0	3.7	3.6	3.4	3.3	3.2	3.1	3.0	2.9	2.9	2.8	2.8	2.7
1.0	1237.8	860.8	668.1	550.4	470.6	412.8	368.9	334.3	306.3	283.2	263.7	247.1	232.7	220.2	209.1	199.2
	6.2	5.3	4.8	4.4	4.2	4.0	3.8	3.7	3.5	3.4	3.4	3.3	3.2	3.1	3.1	3.0

Table F6

Average Daily Radiation (H, kWh/m2) for Month		AC/BC =	0.02
		R =	0.33
		DOD =	0.50

Average Daily Demand (kWh)	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5	8.0	8.5
0.1	118.4	81.7	63.0	51.6	44.0	38.4	34.2	30.9	28.2	26.0	24.2	22.6	21.2	20.1	19.0	18.1
	0.5	0.4	0.3	0.3	0.3	0.3	0.3	0.3	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
0.2	236.8	163.4	126.0	103.3	87.9	76.8	68.4	61.8	56.5	52.1	48.4	45.2	42.5	40.1	38.0	36.2
	0.9	0.8	0.7	0.6	0.6	0.6	0.5	0.5	0.5	0.5	0.5	0.5	0.4	0.4	0.4	0.4
0.3	355.3	245.1	189.1	154.9	131.9	115.3	102.6	92.7	84.7	78.1	72.6	67.8	63.7	60.2	57.0	54.2
	1.4	1.2	1.0	1.0	0.9	0.8	0.8	0.8	0.7	0.7	0.7	0.7	0.7	0.7	0.6	0.6
0.4	473.7	326.8	252.1	206.6	175.9	153.7	136.8	123.6	112.9	104.1	96.7	90.4	85.0	80.2	76.0	72.3
	1.8	1.5	1.4	1.3	1.2	1.1	1.1	1.0	1.0	1.0	0.9	0.9	0.9	0.9	0.9	0.8
0.5	592.1	408.5	315.1	258.2	219.8	192.1	171.0	154.5	141.2	130.2	120.9	113.0	106.2	100.3	95.1	90.4
	2.3	1.9	1.7	1.6	1.5	1.4	1.3	1.3	1.2	1.2	1.2	1.1	1.1	1.1	1.1	1.1
0.6	710.5	490.2	378.1	309.9	263.8	230.5	205.3	185.4	169.4	156.2	145.1	135.7	127.5	120.4	114.1	108.5
	2.7	2.3	2.1	1.9	1.8	1.7	1.6	1.6	1.5	1.5	1.4	1.4	1.3	1.3	1.3	1.3
0.7	828.9	571.9	441.2	361.5	307.8	268.9	239.5	216.3	197.7	182.3	169.3	158.3	148.7	140.4	133.1	126.6
	3.2	2.7	2.4	2.2	2.1	2.0	1.9	1.8	1.7	1.7	1.6	1.6	1.6	1.5	1.5	1.5
0.8	947.4	653.6	504.2	413.2	351.7	307.3	273.7	247.2	225.9	208.3	193.5	180.9	170.0	160.5	152.1	144.7
	3.6	3.1	2.8	2.5	2.4	2.3	2.2	2.1	2.0	1.9	1.9	1.8	1.8	1.8	1.7	1.7
0.9	1065.8	735.4	567.2	464.8	395.7	345.8	307.9	278.1	254.1	234.3	217.7	203.5	191.2	180.5	171.1	162.7
	4.1	3.5	3.1	2.9	2.7	2.5	2.4	2.3	2.2	2.2	2.1	2.1	2.0	2.0	1.9	1.9
1.0	1184.2	817.1	630.2	516.5	439.7	384.2	342.1	309.1	282.4	260.4	241.9	226.1	212.5	200.6	190.1	180.8
	4.5	3.9	3.5	3.2	3.0	2.8	2.7	2.6	2.5	2.4	2.4	2.3	2.2	2.2	2.1	2.1

Table F7

Average Daily Radiation (H, kWh/m2) for Month

AC/BC = 0.02
R = 0.45
DOD = 0.30

Average Daily Demand (kWh)	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5	8.0	8.5
0.1	132.4	93.1	72.9	60.5	52.0	45.9	41.2	37.5	34.5	32.0	29.9	28.1	26.5	25.2	23.9	22.9
	0.9	0.8	0.7	0.7	0.6	0.6	0.6	0.6	0.6	0.5	0.5	0.5	0.5	0.5	0.5	0.5
0.2	264.7	186.2	145.8	120.9	104.0	91.7	82.4	75.0	68.9	64.0	59.8	56.2	53.0	50.3	47.9	45.7
	1.8	1.6	1.4	1.3	1.3	1.2	1.2	1.1	1.1	1.1	1.1	1.0	1.0	1.0	1.0	1.0
0.3	397.1	279.3	218.7	181.4	156.1	137.6	123.5	112.4	103.4	95.9	89.6	84.2	79.6	75.5	71.8	68.6
	2.7	2.4	2.2	2.0	1.9	1.8	1.8	1.7	1.7	1.6	1.6	1.6	1.5	1.5	1.5	1.5
0.4	529.5	372.4	291.5	241.9	208.1	183.5	164.7	149.9	137.9	127.9	119.5	112.3	106.1	100.6	95.8	91.5
	3.6	3.2	2.9	2.7	2.6	2.4	2.4	2.3	2.2	2.2	2.1	2.1	2.0	2.0	2.0	1.9
0.5	661.8	465.5	364.4	302.3	260.1	229.4	205.9	187.4	172.4	159.9	149.4	140.4	132.6	125.8	119.7	114.3
	4.6	4.0	3.6	3.4	3.2	3.1	2.9	2.8	2.8	2.7	2.6	2.6	2.5	2.5	2.5	2.4
0.6	794.2	558.5	437.3	362.8	312.1	275.2	247.1	224.9	206.8	191.9	179.3	168.5	159.1	150.9	143.7	137.2
	5.5	4.8	4.3	4.0	3.8	3.7	3.5	3.4	3.3	3.2	3.2	3.1	3.1	3.0	3.0	2.9
0.7	926.5	651.6	510.2	423.3	364.1	321.1	288.3	262.3	241.3	223.9	209.2	196.5	185.6	176.1	167.6	160.1
	6.4	5.6	5.1	4.7	4.5	4.3	4.1	4.0	3.9	3.8	3.7	3.6	3.6	3.5	3.5	3.4
0.8	1058.9	744.7	583.1	483.7	416.1	367.0	329.5	299.8	275.8	255.9	239.0	224.6	212.1	201.2	191.5	182.9
	7.3	6.3	5.8	5.4	5.1	4.9	4.7	4.6	4.4	4.3	4.2	4.1	4.1	4.0	3.9	3.9
0.9	1191.3	837.8	656.0	544.2	468.2	412.8	370.6	337.3	310.3	287.8	268.9	252.7	238.7	226.4	215.5	205.8
	8.2	7.1	6.5	6.1	5.7	5.5	5.3	5.1	5.0	4.9	4.8	4.7	4.6	4.5	4.4	4.4
1.0	1323.6	930.9	728.8	604.7	520.2	458.7	411.8	374.8	344.7	319.8	298.8	280.8	265.2	251.5	239.4	228.7
	9.1	7.9	7.2	6.7	6.4	6.1	5.9	5.7	5.5	5.4	5.3	5.2	5.1	5.0	4.9	4.9

Table F8

Average Daily Radiation (H, kWh/m2) for Month

AC/BC = 0.02
R = 0.45
DOD = 0.50

Average Daily Demand (kWh)	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5	8.0	8.5
0.1	125.1	87.1	67.7	55.9	47.8	42.0	37.5	34.0	31.2	28.9	26.9	25.2	23.8	22.5	21.4	20.4
	0.7	0.6	0.5	0.5	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.3	0.3	0.3	0.3
0.2	250.1	174.3	135.5	111.7	95.6	83.9	75.1	68.1	62.4	57.7	53.8	50.4	47.5	45.0	42.7	40.7
	1.3	1.1	1.0	1.0	0.9	0.9	0.8	0.8	0.8	0.7	0.7	0.7	0.7	0.7	0.7	0.7
0.3	375.2	261.4	203.2	167.6	143.4	125.9	112.6	102.1	93.6	86.6	80.7	75.7	71.3	67.5	64.1	61.1
	2.0	1.7	1.5	1.4	1.3	1.3	1.2	1.2	1.1	1.1	1.1	1.1	1.0	1.0	1.0	1.0
0.4	500.3	348.5	270.9	223.4	191.2	167.9	150.1	136.2	124.8	115.5	107.6	100.9	95.0	89.9	85.5	81.5
	2.6	2.3	2.1	1.9	1.8	1.7	1.6	1.6	1.5	1.5	1.5	1.4	1.4	1.4	1.3	1.3
0.5	625.3	435.7	338.6	279.3	239.0	209.9	187.7	170.2	156.1	144.4	134.5	126.1	118.8	112.4	106.8	101.8
	3.3	2.8	2.6	2.4	2.2	2.1	2.0	2.0	1.9	1.9	1.8	1.8	1.7	1.7	1.7	1.7
0.6	750.4	522.8	406.4	335.1	286.8	251.8	225.2	204.2	187.3	173.2	161.4	151.3	142.6	134.9	128.2	122.2
	4.0	3.4	3.1	2.9	2.7	2.6	2.5	2.4	2.3	2.2	2.2	2.1	2.1	2.1	2.0	2.0
0.7	875.5	609.9	474.1	391.0	334.6	293.8	262.7	238.3	218.5	202.1	188.3	176.5	166.3	157.4	149.5	142.5
	4.6	4.0	3.6	3.3	3.1	3.0	2.9	2.8	2.7	2.6	2.5	2.5	2.4	2.4	2.4	2.3
0.8	1000.5	697.1	541.8	446.8	382.5	335.8	300.3	272.3	249.7	231.0	215.2	201.7	190.1	179.9	170.9	162.9
	5.3	4.5	4.1	3.8	3.6	3.4	3.3	3.2	3.1	3.0	2.9	2.8	2.8	2.7	2.7	2.6
0.9	1125.6	784.2	609.5	502.7	430.3	377.7	337.8	306.4	280.9	259.8	242.1	227.0	213.8	202.4	192.3	183.3
	5.9	5.1	4.6	4.3	4.0	3.8	3.7	3.6	3.4	3.4	3.3	3.2	3.1	3.1	3.0	3.0
1.0	1250.7	871.3	677.3	558.5	478.1	419.7	375.3	340.4	312.1	288.7	269.0	252.2	237.6	224.9	213.6	203.6
	6.6	5.7	5.1	4.8	4.5	4.3	4.1	4.0	3.8	3.7	3.6	3.6	3.5	3.4	3.4	3.3

Table F9

	Average Daily Radiation (H, kWh/m2) for Month	AC/BC =	0.05
		R =	0.33
		DOD =	0.30

Average Daily Demand (kWh)		1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5	8.0	8.5
	0.1	115.0	78.9	60.6	49.5	42.0	36.6	32.5	29.3	26.7	24.6	22.8	21.3	20.0	18.8	17.8	16.9
		0.9	0.8	0.7	0.6	0.6	0.5	0.5	0.5	0.5	0.5	0.4	0.4	0.4	0.4	0.4	0.4
	0.2	230.1	157.9	121.3	99.0	84.0	73.2	65.0	58.6	53.5	49.2	45.6	42.6	39.9	37.6	35.6	33.8
		1.8	1.5	1.3	1.2	1.2	1.1	1.0	1.0	1.0	0.9	0.9	0.9	0.9	0.8	0.8	0.8
	0.3	345.1	236.8	181.9	148.5	126.0	109.8	97.6	87.9	80.2	73.8	68.4	63.9	59.9	56.5	53.5	50.8
		2.7	2.3	2.0	1.9	1.7	1.6	1.6	1.5	1.4	1.4	1.3	1.3	1.3	1.2	1.2	1.2
	0.4	460.2	315.8	242.5	198.0	168.1	146.4	130.1	117.2	106.9	98.4	91.2	85.1	79.9	75.3	71.3	67.7
		3.6	3.0	2.7	2.5	2.3	2.2	2.1	2.0	1.9	1.8	1.8	1.7	1.7	1.7	1.6	1.6
	0.5	575.2	394.7	303.2	247.6	210.1	183.1	162.6	146.6	133.6	123.0	114.0	106.4	99.9	94.1	89.1	84.6
		4.5	3.8	3.4	3.1	2.9	2.7	2.6	2.5	2.4	2.3	2.2	2.2	2.1	2.1	2.0	2.0
	0.6	690.2	473.7	363.8	297.1	252.1	219.7	195.1	175.9	160.4	147.6	136.8	127.7	119.8	112.9	106.9	101.5
		5.4	4.5	4.0	3.7	3.5	3.3	3.1	3.0	2.9	2.8	2.7	2.6	2.6	2.5	2.4	2.4
	0.7	805.3	552.6	424.4	346.6	294.1	256.3	227.6	205.2	187.1	172.2	159.6	149.0	139.8	131.8	124.7	118.5
		6.3	5.3	4.7	4.3	4.0	3.8	3.6	3.5	3.3	3.2	3.1	3.1	3.0	2.9	2.8	2.8
	0.8	920.3	631.6	485.1	396.1	336.1	292.9	260.2	234.5	213.8	196.8	182.5	170.3	159.8	150.6	142.5	135.4
		7.1	6.0	5.4	4.9	4.6	4.3	4.1	4.0	3.8	3.7	3.6	3.5	3.4	3.3	3.3	3.2
	0.9	1035.4	710.5	545.7	445.6	378.1	329.5	292.7	263.8	240.5	221.4	205.3	191.6	179.7	169.4	160.4	152.3
		8.0	6.8	6.1	5.6	5.2	4.9	4.7	4.5	4.3	4.2	4.0	3.9	3.8	3.7	3.7	3.6
	1.0	1150.4	789.5	606.3	495.1	420.2	366.1	325.2	293.1	267.3	245.9	228.1	212.8	199.7	188.2	178.2	169.2
		8.9	7.6	6.7	6.2	5.8	5.4	5.2	5.0	4.8	4.6	4.5	4.4	4.3	4.2	4.1	4.0

Table F10

Average Daily Radiation (H, kWh/m2) for Month

AC/BC = 0.05
R = 0.33
DOD = 0.50

Average Daily Demand (kWh)	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5	8.0	8.5
0.1	111.6	76.2	58.2	47.4	40.1	34.8	30.8	27.7	25.2	23.1	21.4	20.0	18.7	17.6	16.6	15.8
	0.7	0.6	0.5	0.5	0.4	0.4	0.4	0.4	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
0.2	223.3	152.4	116.5	94.7	80.1	69.6	61.6	55.4	50.4	46.3	42.8	39.9	37.4	35.2	33.2	31.5
	1.3	1.1	1.0	0.9	0.8	0.8	0.8	0.7	0.7	0.7	0.6	0.6	0.6	0.6	0.6	0.6
0.3	334.9	228.5	174.7	142.1	120.2	104.4	92.5	83.1	75.6	69.4	64.3	59.9	56.1	52.8	49.9	47.3
	2.0	1.7	1.5	1.4	1.3	1.2	1.1	1.1	1.0	1.0	1.0	0.9	0.9	0.9	0.9	0.9
0.4	446.6	304.7	232.9	189.5	160.2	139.2	123.3	110.9	100.8	92.6	85.7	79.8	74.8	70.3	66.5	63.0
	2.7	2.2	2.0	1.8	1.7	1.6	1.5	1.4	1.4	1.3	1.3	1.3	1.2	1.2	1.2	1.1
0.5	558.2	380.9	291.2	236.8	200.3	174.0	154.1	138.6	126.0	115.7	107.1	99.8	93.4	87.9	83.1	78.8
	3.3	2.8	2.5	2.3	2.1	2.0	1.9	1.8	1.7	1.7	1.6	1.6	1.5	1.5	1.5	1.4
0.6	669.9	457.1	349.4	284.2	240.4	208.8	184.9	166.3	151.3	138.9	128.5	119.7	112.1	105.5	99.7	94.6
	4.0	3.4	3.0	2.7	2.5	2.4	2.3	2.2	2.1	2.0	1.9	1.9	1.8	1.8	1.7	1.7
0.7	781.5	533.2	407.7	331.6	280.4	243.6	215.8	194.0	176.5	162.0	150.0	139.7	130.8	123.1	116.3	110.3
	4.7	3.9	3.5	3.2	2.9	2.8	2.6	2.5	2.4	2.3	2.3	2.2	2.1	2.1	2.0	2.0
0.8	893.2	609.4	465.9	378.9	320.5	278.4	246.6	221.7	201.7	185.2	171.4	159.6	149.5	140.7	132.9	126.1
	5.3	4.5	4.0	3.6	3.4	3.2	3.0	2.9	2.8	2.7	2.6	2.5	2.4	2.4	2.3	2.3
0.9	1004.8	685.6	524.1	426.3	360.5	313.2	277.4	249.4	226.9	208.3	192.8	179.6	168.2	158.3	149.6	141.8
	6.0	5.0	4.5	4.1	3.8	3.6	3.4	3.2	3.1	3.0	2.9	2.8	2.7	2.7	2.6	2.6
1.0	1116.5	761.8	582.4	473.7	400.6	348.0	308.2	277.1	252.1	231.5	214.2	199.5	186.9	175.9	166.2	157.6
	6.7	5.6	5.0	4.5	4.2	4.0	3.8	3.6	3.5	3.3	3.2	3.1	3.0	3.0	2.9	2.8

Table F11

Average Daily Radiation (H, kWh/m2) for Month

AC/BC = 0.05
R = 0.45
DOD = 0.30

Average Daily Demand (kWh)	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5	8.0	8.5
0.1	120.5	83.4	64.5	52.9	45.2	39.5	35.2	31.9	29.2	26.9	25.0	23.4	22.0	20.8	19.7	18.8
	1.3	1.1	1.0	0.9	0.9	0.8	0.8	0.7	0.7	0.7	0.7	0.7	0.7	0.6	0.6	0.6
0.2	240.9	166.8	128.9	105.9	90.3	79.0	70.5	63.7	58.3	53.8	50.0	46.8	44.0	41.6	39.5	37.6
	2.6	2.2	2.0	1.8	1.7	1.6	1.6	1.5	1.4	1.4	1.4	1.3	1.3	1.3	1.3	1.2
0.3	361.4	250.1	193.4	158.8	135.5	118.5	105.7	95.6	87.5	80.7	75.1	70.2	66.1	62.4	59.2	56.4
	3.9	3.3	3.0	2.7	2.6	2.4	2.3	2.2	2.2	2.1	2.0	2.0	2.0	1.9	1.9	1.8
0.4	481.9	333.5	257.9	211.8	180.6	158.0	140.9	127.5	116.6	107.6	100.1	93.7	88.1	83.2	78.9	75.1
	5.2	4.4	4.0	3.6	3.4	3.2	3.1	3.0	2.9	2.8	2.7	2.7	2.6	2.6	2.5	2.5
0.5	602.3	416.9	322.4	264.7	225.8	197.6	176.2	159.4	145.8	134.5	125.1	117.1	110.1	104.0	98.7	93.9
	6.4	5.5	4.9	4.6	4.3	4.1	3.9	3.7	3.6	3.5	3.4	3.3	3.3	3.2	3.1	3.1
0.6	722.8	500.3	386.8	317.7	270.9	237.1	211.4	191.2	174.9	161.5	150.1	140.5	132.1	124.8	118.4	112.7
	7.7	6.6	5.9	5.5	5.1	4.9	4.7	4.5	4.3	4.2	4.1	4.0	3.9	3.8	3.8	3.7
0.7	843.3	583.7	451.3	370.6	316.1	276.6	246.6	223.1	204.1	188.4	175.2	163.9	154.2	145.7	138.2	131.5
	9.0	7.7	6.9	6.4	6.0	5.7	5.4	5.2	5.1	4.9	4.8	4.7	4.6	4.5	4.4	4.3
0.8	963.7	667.0	515.8	423.6	361.2	316.1	281.9	255.0	233.2	215.3	200.2	187.3	176.2	166.5	157.9	150.3
	10.3	8.8	7.9	7.3	6.8	6.5	6.2	6.0	5.8	5.6	5.5	5.3	5.2	5.1	5.0	4.9
0.9	1084.2	750.4	580.3	476.5	406.4	355.6	317.1	286.8	262.4	242.2	225.2	210.7	198.2	187.3	177.6	169.1
	11.6	9.9	8.9	8.2	7.7	7.3	7.0	6.7	6.5	6.3	6.1	6.0	5.9	5.7	5.6	5.5
1.0	1204.7	833.8	644.7	529.5	451.5	395.1	352.3	318.7	291.5	269.1	250.2	234.1	220.2	208.1	197.4	187.9
	12.9	11.0	9.9	9.1	8.6	8.1	7.8	7.5	7.2	7.0	6.8	6.7	6.5	6.4	6.3	6.2

Table F12

Average Daily Radiation (H, kWh/m2) for Month

AC/BC = 0.05
R = 0.45
DOD = 0.50

Average Daily Demand (kWh)	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5	8.0	8.5
0.1	115.9	79.6	61.2	50.0	42.5	37.0	32.9	29.7	27.1	24.9	23.1	21.6	20.3	19.1	18.1	17.2
	1.0	0.8	0.7	0.7	0.6	0.6	0.6	0.5	0.5	0.5	0.5	0.5	0.5	0.4	0.4	0.4
0.2	231.7	159.2	122.4	100.1	85.0	74.1	65.9	59.4	54.2	49.9	46.3	43.2	40.6	38.2	36.2	34.4
	1.9	1.6	1.4	1.3	1.2	1.2	1.1	1.1	1.0	1.0	1.0	0.9	0.9	0.9	0.9	0.9
0.3	347.6	238.8	183.6	150.1	127.5	111.1	98.8	89.1	81.3	74.8	69.4	64.8	60.8	57.4	54.3	51.6
	2.9	2.4	2.2	2.0	1.8	1.7	1.7	1.6	1.5	1.5	1.4	1.4	1.4	1.3	1.3	1.3
0.4	463.4	318.4	244.8	200.1	169.9	148.2	131.7	118.8	108.4	99.8	92.6	86.4	81.1	76.5	72.4	68.8
	3.8	3.2	2.9	2.6	2.5	2.3	2.2	2.1	2.1	2.0	1.9	1.9	1.8	1.8	1.8	1.7
0.5	579.3	398.1	306.1	250.1	212.4	185.2	164.6	148.5	135.5	124.7	115.7	108.0	101.4	95.6	90.5	86.0
	4.8	4.0	3.6	3.3	3.1	2.9	2.8	2.7	2.6	2.5	2.4	2.3	2.3	2.2	2.2	2.2
0.6	695.1	477.7	367.3	300.2	254.9	222.3	197.6	178.2	162.5	149.7	138.8	129.6	121.7	114.7	108.6	103.2
	5.7	4.8	4.3	4.0	3.7	3.5	3.3	3.2	3.1	3.0	2.9	2.8	2.8	2.7	2.6	2.6
0.7	811.0	557.3	428.5	350.2	297.4	259.3	230.5	207.9	189.6	174.6	162.0	151.2	141.9	133.9	126.7	120.4
	6.7	5.6	5.0	4.6	4.3	4.1	3.9	3.7	3.6	3.5	3.4	3.3	3.2	3.1	3.1	3.0
0.8	926.8	636.9	489.7	400.2	339.9	296.4	263.4	237.6	216.7	199.5	185.1	172.8	162.2	153.0	144.8	137.6
	7.6	6.4	5.8	5.3	4.9	4.7	4.4	4.3	4.1	4.0	3.9	3.8	3.7	3.6	3.5	3.4
0.9	1042.7	716.5	550.9	450.2	382.4	333.4	296.3	267.3	243.8	224.5	208.3	194.4	182.5	172.1	162.9	154.8
	8.6	7.3	6.5	5.9	5.5	5.2	5.0	4.8	4.6	4.5	4.3	4.2	4.1	4.0	4.0	3.9
1.0	1158.5	796.1	612.1	500.3	424.9	370.5	329.3	297.0	270.9	249.4	231.4	216.0	202.8	191.2	181.1	172.0
	9.5	8.1	7.2	6.6	6.2	5.8	5.6	5.3	5.1	5.0	4.8	4.7	4.6	4.5	4.4	4.3

Table F13

Average Daily Radiation (H, kWh/m2) for Month	AC/BC =	0.10
	R =	0.33
	DOD =	0.30

Average Daily Demand (kWh)

	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5	8.0	8.5
0.1	110.6	75.3	57.5	46.7	39.5	34.3	30.3	27.2	24.8	22.7	21.0	19.6	18.3	17.2	16.3	15.4
	1.2	1.0	0.9	0.8	0.8	0.7	0.7	0.6	0.6	0.6	0.6	0.6	0.5	0.5	0.5	0.5
0.2	221.3	150.7	115.0	93.5	78.9	68.5	60.6	54.5	49.5	45.4	42.0	39.1	36.6	34.4	32.5	30.8
	2.4	2.0	1.8	1.6	1.5	1.4	1.3	1.3	1.2	1.2	1.2	1.1	1.1	1.1	1.0	1.0
0.3	331.9	226.0	172.6	140.2	118.4	102.8	91.0	81.7	74.3	68.1	63.0	58.7	54.9	51.6	48.8	46.2
	3.6	3.0	2.7	2.4	2.3	2.1	2.0	1.9	1.9	1.8	1.7	1.7	1.6	1.6	1.6	1.5
0.4	442.5	301.4	230.1	186.9	157.9	137.0	121.3	108.9	99.0	90.9	84.0	78.2	73.2	68.9	65.0	61.6
	4.8	4.0	3.6	3.3	3.0	2.8	2.7	2.6	2.5	2.4	2.3	2.2	2.2	2.1	2.1	2.0
0.5	553.2	376.7	287.6	233.6	197.4	171.3	151.6	136.2	123.8	113.6	105.0	97.8	91.5	86.1	81.3	77.1
	6.0	5.0	4.5	4.1	3.8	3.5	3.4	3.2	3.1	3.0	2.9	2.8	2.7	2.6	2.6	2.5
0.6	663.8	452.1	345.1	280.4	236.8	205.5	181.9	163.4	148.5	136.3	126.0	117.3	109.8	103.3	97.6	92.5
	7.2	6.1	5.4	4.9	4.5	4.3	4.0	3.9	3.7	3.6	3.5	3.3	3.3	3.2	3.1	3.0
0.7	774.4	527.4	402.6	327.1	276.3	239.8	212.2	190.6	173.3	159.0	147.1	136.9	128.1	120.5	113.8	107.9
	8.4	7.1	6.3	5.7	5.3	5.0	4.7	4.5	4.3	4.2	4.0	3.9	3.8	3.7	3.6	3.5
0.8	885.1	602.8	460.2	373.8	315.8	274.0	242.5	217.9	198.0	181.7	168.1	156.4	146.4	137.7	130.1	123.3
	9.6	8.1	7.1	6.5	6.0	5.7	5.4	5.1	4.9	4.8	4.6	4.5	4.3	4.2	4.1	4.0
0.9	995.7	678.1	517.7	420.5	355.3	308.3	272.9	245.1	222.8	204.4	189.1	176.0	164.7	154.9	146.3	138.7
	10.8	9.1	8.0	7.3	6.8	6.4	6.1	5.8	5.6	5.4	5.2	5.0	4.9	4.8	4.7	4.6
1.0	1106.3	753.5	575.2	467.3	394.7	342.6	303.2	272.4	247.6	227.2	210.1	195.6	183.1	172.2	162.6	154.1
	12.0	10.1	8.9	8.1	7.6	7.1	6.7	6.4	6.2	5.9	5.8	5.6	5.4	5.3	5.2	5.1

Table F14

Average Daily Radiation (H, kWh/m2) for Month

AC/BC = 0.10
R = 0.33
DOD = 0.50

Average Daily Demand (kWh)	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5	8.0	8.5
0.1	108.2	73.4	55.8	45.2	38.1	33.0	29.1	26.1	23.7	21.7	20.0	18.6	17.4	16.3	15.4	14.6
	0.9	0.8	0.7	0.6	0.6	0.5	0.5	0.5	0.5	0.4	0.4	0.4	0.4	0.4	0.4	0.4
0.2	216.5	146.8	111.6	90.4	76.2	65.9	58.2	52.2	47.4	43.4	40.1	37.2	34.8	32.7	30.8	29.2
	1.8	1.5	1.3	1.2	1.1	1.1	1.0	0.9	0.9	0.9	0.8	0.8	0.8	0.8	0.8	0.7
0.3	324.7	220.2	167.5	135.6	114.3	98.9	87.4	78.3	71.1	65.1	60.1	55.8	52.2	49.0	46.2	43.8
	2.7	2.3	2.0	1.8	1.7	1.6	1.5	1.4	1.4	1.3	1.3	1.2	1.2	1.2	1.1	1.1
0.4	432.9	293.6	223.3	180.8	152.4	131.9	116.5	104.4	94.7	86.8	80.1	74.5	69.6	65.4	61.6	58.4
	3.6	3.0	2.7	2.4	2.2	2.1	2.0	1.9	1.8	1.7	1.7	1.6	1.6	1.5	1.5	1.5
0.5	541.2	367.0	279.1	226.0	190.4	164.9	145.6	130.5	118.4	108.5	100.1	93.1	87.0	81.7	77.1	73.0
	4.5	3.8	3.3	3.0	2.8	2.6	2.5	2.4	2.3	2.2	2.1	2.0	2.0	1.9	1.9	1.8
0.6	649.4	440.4	334.9	271.3	228.5	197.8	174.7	156.6	142.1	130.2	120.2	111.7	104.4	98.0	92.5	87.5
	5.5	4.5	4.0	3.6	3.4	3.2	3.0	2.8	2.7	2.6	2.5	2.4	2.4	2.3	2.3	2.2
0.7	757.7	513.7	390.8	316.5	266.6	230.8	203.8	182.7	165.8	151.9	140.2	130.3	121.8	114.4	107.9	102.1
	6.4	5.3	4.7	4.2	3.9	3.7	3.5	3.3	3.2	3.1	2.9	2.9	2.8	2.7	2.6	2.6
0.8	865.9	587.1	446.6	361.7	304.7	263.8	232.9	208.8	189.5	173.6	160.2	148.9	139.2	130.7	123.3	116.7
	7.3	6.1	5.3	4.8	4.5	4.2	4.0	3.8	3.6	3.5	3.4	3.3	3.2	3.1	3.0	2.9
0.9	974.1	660.5	502.4	406.9	342.8	296.8	262.1	234.9	213.2	195.2	180.3	167.5	156.6	147.1	138.7	131.3
	8.2	6.8	6.0	5.5	5.0	4.7	4.5	4.3	4.1	3.9	3.8	3.7	3.6	3.5	3.4	3.3
1.0	1082.4	733.9	558.2	452.1	380.9	329.7	291.2	261.1	236.8	216.9	200.3	186.2	174.0	163.4	154.1	145.9
	9.1	7.6	6.7	6.1	5.6	5.3	5.0	4.7	4.5	4.4	4.2	4.1	4.0	3.9	3.8	3.7

Table F15

Average Daily Radiation (H, kWh/m2) for Month

AC/BC = 0.10
R = 0.45
DOD = 0.30

Average Daily Demand (kWh)	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5	8.0	8.5
0.1	114.5	78.5	60.2	49.2	41.7	36.3	32.2	29.0	26.5	24.4	22.6	21.1	19.8	18.6	17.6	16.7
	1.7	1.4	1.3	1.2	1.1	1.0	1.0	0.9	0.9	0.9	0.9	0.8	0.8	0.8	0.8	0.8
0.2	228.9	157.0	120.5	98.3	83.4	72.6	64.5	58.1	52.9	48.7	45.2	42.1	39.5	37.2	35.2	33.5
	3.4	2.9	2.6	2.4	2.2	2.1	2.0	1.9	1.8	1.8	1.7	1.7	1.6	1.6	1.6	1.5
0.3	343.4	235.5	180.7	147.5	125.1	108.9	96.7	87.1	79.4	73.1	67.7	63.2	59.3	55.9	52.9	50.2
	5.1	4.3	3.9	3.5	3.3	3.1	3.0	2.8	2.7	2.6	2.6	2.5	2.4	2.4	2.3	2.3
0.4	457.9	313.9	240.9	196.6	166.8	145.2	128.9	116.2	105.9	97.4	90.3	84.2	79.0	74.5	70.5	66.9
	6.8	5.8	5.2	4.7	4.4	4.2	4.0	3.8	3.6	3.5	3.4	3.3	3.2	3.2	3.1	3.0
0.5	572.4	392.4	301.2	245.8	208.4	181.5	161.2	145.2	132.4	121.8	112.9	105.3	98.8	93.1	88.1	83.6
	8.6	7.2	6.4	5.9	5.5	5.2	4.9	4.7	4.6	4.4	4.3	4.2	4.1	4.0	3.9	3.8
0.6	686.8	470.9	361.4	294.9	250.1	217.8	193.4	174.3	158.8	146.1	135.5	126.4	118.5	111.7	105.7	100.4
	10.3	8.7	7.7	7.1	6.6	6.2	5.9	5.7	5.5	5.3	5.1	5.0	4.9	4.8	4.7	4.6
0.7	801.3	549.4	421.6	344.1	291.8	254.2	225.7	203.3	185.3	170.5	158.0	147.4	138.3	130.3	123.3	117.1
	12.0	10.1	9.0	8.3	7.7	7.3	6.9	6.6	6.4	6.2	6.0	5.8	5.7	5.6	5.4	5.3
0.8	915.8	627.9	481.9	393.2	333.5	290.5	257.9	232.4	211.8	194.8	180.6	168.5	158.0	148.9	140.9	133.8
	13.7	11.6	10.3	9.4	8.8	8.3	7.9	7.6	7.3	7.1	6.8	6.7	6.5	6.3	6.2	6.1
0.9	1030.3	706.4	542.1	442.4	375.2	326.8	290.1	261.4	238.3	219.2	203.2	189.6	177.8	167.6	158.6	150.6
	15.4	13.0	11.6	10.6	9.9	9.3	8.9	8.5	8.2	7.9	7.7	7.5	7.3	7.1	7.0	6.9
1.0	1144.7	784.8	602.3	491.5	416.9	363.1	322.4	290.4	264.7	243.5	225.8	210.6	197.6	186.2	176.2	167.3

Table 16

Average Daily Radiation (H, kWh/m2) for Month

AC/BC = 0.10
R = 0.45
DOD = 0.50

Average Daily Demand (kWh)	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5	8.0	8.5
0.1	111.2	75.8	57.9	47.1	39.8	34.6	30.6	27.5	25.0	23.0	21.2	19.8	18.5	17.4	16.5	15.6
	1.3	1.1	1.0	0.9	0.8	0.8	0.7	0.7	0.7	0.6	0.6	0.6	0.6	0.6	0.6	0.5
0.2	222.4	151.6	115.9	94.2	79.6	69.1	61.2	55.0	50.0	45.9	42.5	39.6	37.0	34.9	32.9	31.2
	2.6	2.1	1.9	1.7	1.6	1.5	1.4	1.4	1.3	1.3	1.2	1.2	1.2	1.1	1.1	1.1
0.3	333.6	227.5	173.8	141.3	119.4	103.7	91.8	82.5	75.0	68.9	63.7	59.3	55.6	52.3	49.4	46.8
	3.8	3.2	2.9	2.6	2.4	2.3	2.2	2.1	2.0	1.9	1.8	1.8	1.7	1.7	1.7	1.6
0.4	444.8	303.3	231.7	188.4	159.2	138.3	122.4	110.0	100.1	91.8	85.0	79.1	74.1	69.7	65.9	62.4
	5.1	4.3	3.8	3.5	3.2	3.0	2.9	2.7	2.6	2.5	2.5	2.4	2.3	2.3	2.2	2.2
0.5	556.1	379.1	289.6	235.5	199.0	172.8	153.0	137.5	125.1	114.8	106.2	98.9	92.6	87.1	82.3	78.0
	6.4	5.4	4.8	4.3	4.0	3.8	3.6	3.4	3.3	3.2	3.1	3.0	2.9	2.8	2.8	2.7
0.6	667.3	454.9	347.6	282.5	238.8	207.4	183.6	165.0	150.1	137.8	127.5	118.7	111.1	104.6	98.8	93.7
	7.7	6.4	5.7	5.2	4.8	4.5	4.3	4.1	4.0	3.8	3.7	3.6	3.5	3.4	3.3	3.3
0.7	778.5	530.7	405.5	329.6	278.6	241.9	214.2	192.5	175.1	160.7	148.7	138.5	129.7	122.0	115.2	109.3
	9.0	7.5	6.7	6.1	5.6	5.3	5.0	4.8	4.6	4.5	4.3	4.2	4.1	4.0	3.9	3.8
0.8	889.7	606.6	463.4	376.7	318.4	276.5	244.8	220.1	200.1	183.7	169.9	158.3	148.2	139.4	131.7	124.9
	10.2	8.6	7.6	6.9	6.4	6.1	5.8	5.5	5.3	5.1	4.9	4.8	4.7	4.5	4.4	4.3
0.9	1000.9	682.4	521.3	423.8	358.3	311.1	275.4	247.6	225.1	206.7	191.2	178.0	166.7	156.8	148.2	140.5
	11.5	9.7	8.6	7.8	7.3	6.8	6.5	6.2	5.9	5.7	5.5	5.4	5.2	5.1	5.0	4.9
1.0	1112.1	758.2	579.3	470.9	398.1	345.6	306.1	275.1	250.1	229.6	212.4	197.8	185.2	174.3	164.6	156.1
	12.8	10.7	9.5	8.7	8.1	7.6	7.2	6.9	6.6	6.4	6.2	6.0	5.8	5.7	5.6	5.4

Appendix G: Power Produced by Specified Turbine per annum (kWh)

Table G1

Turbine Characteristics

Cut-in Velocity = 3 m/s
Rated Velocity = 7 m/s
Furling Velocity = 15 m/s

Turbine Rated Pwr (kW)	Average Wind Velocity (m/s) 3	4	5	6	7	8	9	10
0.5	930	1700	2330	2770	3020	3110	3080	2970
1.0	1870	3410	4660	5540	6040	6230	6160	5930
1.5	2800	5110	6980	8310	9060	9340	9250	8900
2.0	3730	6810	9310	11080	12080	12450	12330	11870
2.5	4660	8510	11640	13850	15100	15570	15410	14830
3.0	5600	10220	13970	16620	18120	18680	18490	17800
3.5	6530	11920	16300	19380	21140	21790	21580	20760
4.0	7460	13620	18620	22150	24160	24900	24660	23730
4.5	8400	15320	20950	24920	27180	28020	27740	26700
5.0	9329	17027	23280	27693	30200	31131	30824	29664
5.5	10260	18730	25610	30460	33220	34240	33910	32630
6.0	11200	20430	27940	33230	36240	37360	36990	35600
6.5	12130	22140	30260	36000	39260	40470	40070	38560
7.0	13060	23840	32590	38770	42280	43580	43150	41530
7.5	13990	25540	34920	41540	45300	46700	46240	44500
8.0	14930	27240	37250	44310	48320	49810	49320	47460
8.5	15860	28950	39580	47080	51340	52920	52400	50430
9.0	16790	30650	41900	49850	54360	56040	55480	53390
9.5	17730	32350	44230	52620	57380	59150	58570	56360
10.0	18660	34050	46560	55390	60400	62260	61650	59330

Table G2

Turbine Characteristics

Cut-in Velocity = 3 m/s
Rated Velocity = 7 m/s
Furling Velocity = 20 m/s

Turbine Rated Pwr (kW)	Average Wind Velocity (m/s) 3	4	5	6	7	8	9	10
0.5	930	1700	2330	2800	3130	3350	3480	3520
1.0	1870	3410	4660	5600	6260	6710	6960	7050
1.5	2800	5110	7000	8400	9390	10060	10440	10570
2.0	3730	6810	9330	11200	12520	13420	13920	14090
2.5	4660	8510	11660	14000	15650	16770	17410	17610
3.0	5600	10220	13990	16800	18780	20120	20890	21140
3.5	6530	11920	16330	19600	21910	23480	24370	24660
4.0	7460	13620	18660	22400	25040	26830	27850	28180
4.5	8400	15320	20990	25200	28170	30190	31330	31700
5.0	9329	17027	23323	27999	31295	33540	34810	35226
5.5	10260	18730	25660	30800	34420	36890	38290	38750
6.0	11200	20430	27990	33600	37550	40250	41770	42270
6.5	12130	22140	30320	36400	40680	43600	45250	45790
7.0	13060	23840	32650	39200	43810	46960	48730	49320
7.5	13990	25540	34990	42000	46940	50310	52220	52840
8.0	14930	27240	37320	44800	50070	53660	55700	56360
8.5	15860	28950	39650	47600	53200	57020	59180	59880
9.0	16790	30650	41980	50400	56330	60370	62660	63410
9.5	17730	32350	44310	53200	59460	63730	66140	66930
10.0	18660	34050	46650	56000	62590	67080	69620	70450

Table G3

Turbine Characteristics

Cut-in Velocity = 3 m/s
Rated Velocity = 9 m/s
Furling Velocity = 15 m/s

Turbine Rated Pwr (kW)	Average Wind Velocity (m/s) 3	4	5	6	7	8	9	10
0.5	640	1230	1800	2260	2570	2710	2740	2670
1.0	1270	2460	3600	4530	5130	5430	5470	5330
1.5	1910	3690	5410	6790	7700	8140	8210	8000
2.0	2540	4920	7210	9050	10260	10860	10950	10670
2.5	3180	6150	9010	11320	12830	13570	13680	13330
3.0	3810	7380	10810	13580	15390	16290	16420	16000
3.5	4450	8620	12620	15850	17960	19000	19160	18670
4.0	5080	9850	14420	18110	20520	21720	21890	21330
4.5	5720	11080	16220	20370	23090	24430	24630	24000
5.0	6351	12308	18024	22637	25652	27149	27368	26667
5.5	6990	13540	19830	24900	28220	29860	30100	29330
6.0	7620	14770	21630	27160	30780	32580	32840	32000
6.5	8260	16000	23430	29430	33350	35290	35580	34670
7.0	8890	17230	25230	31690	35910	38010	38310	37330
7.5	9530	18460	27040	33960	38480	40720	41050	40000
8.0	10160	19690	28840	36220	41040	43440	43790	42670
8.5	10800	20920	30640	38480	43610	46150	46530	45330
9.0	11430	22150	32440	40750	46170	48870	49260	48000
9.5	12070	23380	34250	43010	48740	51580	52000	50670
10.0	12700	24620	36050	45270	51300	54300	54740	53330

Table G4

Turbine Characteristics

Cut-in Velocity = 3 m/s
Rated Velocity = 9 m/s
Furling Velocity = 20 m/s

Turbine Rated Pwr (kW)	Average Wind Velocity (m/s) 3	4	5	6	7	8	9	10
0.5	640	1230	1810	2290	2670	2960	3140	3220
1.0	1270	2460	3610	4590	5350	5910	6270	6450
1.5	1910	3690	5420	6880	8020	8870	9410	9670
2.0	2540	4920	7230	9180	10700	11820	12540	12890
2.5	3180	6150	9030	11470	13370	14780	15680	16110
3.0	3810	7380	10840	13770	16050	17730	18810	19340
3.5	4450	8620	12650	16060	18720	20690	21950	22560
4.0	5080	9850	14450	18360	21400	23650	25080	25780
4.5	5720	11080	16260	20650	24070	26600	28220	29010
5.0	6351	12308	18068	22944	26747	29558	31354	32230
5.5	6990	13540	19870	25240	29420	32510	34490	35450
6.0	7620	14770	21680	27530	32100	35470	37620	38680
6.5	8260	16000	23490	29830	34770	38430	40760	41900
7.0	8890	17230	25290	32120	37450	41380	43890	45120
7.5	9530	18460	27100	34420	40120	44340	47030	48340
8.0	10160	19690	28910	36710	42800	47290	50170	51570
8.5	10800	20920	30710	39000	45470	50250	53300	54790
9.0	11430	22150	32520	41300	48140	53200	56440	58010
9.5	12070	23380	34330	43590	50820	56160	59570	61240
10.0	12700	24620	36140	45890	53490	59120	62710	64460

Table G5

Turbine Characteristics

Cut-in Velocity = 3 m/s
Rated Velocity = 11 m/s
Furling Velocity = 15 m/s

Turbine Rated Pwr (kW)	Average Wind Velocity (m/s) 3	4	5	6	7	8	9	10
0.5	480	940	1420	1840	2150	2330	2390	2350
1.0	950	1870	2830	3690	4300	4660	4770	4700
1.5	1430	2810	4250	5530	6460	6990	7160	7060
2.0	1910	3750	5660	7370	8610	9320	9540	9410
2.5	2380	4680	7080	9220	10760	11650	11930	11760
3.0	2860	5620	8500	11060	12910	13970	14320	14110
3.5	3340	6560	9910	12900	15060	16300	16700	16460
4.0	3810	7490	11330	14750	17210	18630	19090	18820
4.5	4290	8430	12740	16590	19370	20960	21470	21170
5.0	4769	9368	14158	18434	21517	23291	23860	23521
5.5	5250	10300	15570	20280	23670	25620	26250	25870
6.0	5720	11240	16990	22120	25820	27950	28630	28220
6.5	6200	12180	18410	23960	27970	30280	31020	30580
7.0	6680	13110	19820	25810	30120	32610	33400	32930
7.5	7150	14050	21240	27650	32280	34940	35790	35280
8.0	7630	14990	22650	29490	34430	37270	38180	37630
8.5	8110	15930	24070	31340	36580	39590	40560	39990
9.0	8580	16860	25490	33180	38730	41920	42950	42340
9.5	9060	17800	26900	35030	40880	44250	45330	44690
10.0	9540	18740	28320	36870	43030	46580	47720	47040

Table G6

Turbine Characteristics

Cut-in Velocity = 3 m/s
Rated Velocity = 11 m/s
Furling Velocity = 20 m/s

Turbine Rated Pwr (kW)	Average Wind Velocity (m/s) 3	4	5	6	7	8	9	10
0.5	480	940	1420	1870	2260	2570	2780	2910
1.0	950	1870	2840	3750	4520	5140	5570	5820
1.5	1430	2810	4260	5620	6780	7710	8350	8720
2.0	1910	3750	5680	7500	9040	10280	11140	11630
2.5	2380	4680	7100	9370	11310	12850	13920	14540
3.0	2860	5620	8520	11240	13570	15420	16710	17450
3.5	3340	6560	9940	13120	15830	17990	19490	20360
4.0	3810	7490	11360	14990	18090	20560	22280	23270
4.5	4290	8430	12780	16870	20350	23130	25060	26170
5.0	4769	9368	14202	18741	22612	25700	27846	29083
5.5	5250	10300	15620	20620	24870	28270	30630	31990
6.0	5720	11240	17040	22490	27130	30840	33420	34900
6.5	6200	12180	18460	24360	29400	33410	36200	37810
7.0	6680	13110	19880	26240	31660	35980	38980	40720
7.5	7150	14050	21300	28110	33920	38550	41770	43620
8.0	7630	14990	22720	29990	36180	41120	44550	46530
8.5	8110	15930	24140	31860	38440	43690	47340	49440
9.0	8580	16860	25560	33730	40700	46260	50120	52350
9.5	9060	17800	26980	35610	42960	48830	52910	55260
10.0	9540	18740	28400	37480	45220	51400	55690	58170

Table G7

Turbine Characteristics

Cut-in Velocity = 4 m/s
Rated Velocity = 8 m/s
Furling Velocity = 15 m/s

Turbine Rated Pwr	Average Wind Velocity (m/s)							
(kW)	3	4	5	6	7	8	9	10
0.5	450	1100	1740	2240	2570	2730	2760	2690
1.0	900	2200	3480	4490	5140	5460	5520	5380
1.5	1350	3290	5210	6730	7710	8190	8270	8070
2.0	1800	4390	6950	8970	10280	10920	11030	10760
2.5	2260	5490	8690	11220	12850	13650	13790	13450
3.0	2710	6590	10430	13460	15420	16390	16550	16140
3.5	3160	7690	12160	15710	17990	19120	19310	18830
4.0	3610	8790	13900	17950	20560	21850	22070	21520
4.5	4060	9880	15640	20190	23130	24580	24820	24210
5.0	4511	10983	17378	22437	25700	27309	27583	26904
5.5	4960	12080	19120	24680	28270	30040	30340	29590
6.0	5410	13180	20850	26920	30840	32770	33100	32280
6.5	5860	14280	22590	29170	33410	35500	35860	34980
7.0	6320	15380	24330	31410	35980	38230	38620	37670
7.5	6770	16470	26070	33650	38550	40960	41370	40360
8.0	7220	17570	27800	35900	41120	43690	44130	43050
8.5	7670	18670	29540	38140	43690	46430	46890	45740
9.0	8120	19770	31280	40390	46260	49160	49650	48430
9.5	8570	20870	33020	42630	48830	51890	52410	51120
10.0	9020	21970	34760	44870	51400	54620	55170	53810

Table G8

Turbine Characteristics

Cut-in Velocity = 4 m/s
Rated Velocity = 8 m/s
Furling Velocity = 20 m/s

Turbine Rated Pwr	Average Wind Velocity (m/s)							
(kW)	3	4	5	6	7	8	9	10
0.5	450	1100	1740	2270	2680	2970	3160	3250
1.0	900	2200	3480	4550	5360	5940	6310	6490
1.5	1350	3290	5230	6820	8040	8920	9470	9740
2.0	1800	4390	6970	9100	10720	11890	12630	12990
2.5	2260	5490	8710	11370	13400	14860	15780	16230
3.0	2710	6590	10450	13650	16080	17830	18940	19480
3.5	3160	7690	12200	15920	18760	20800	22100	22730
4.0	3610	8790	13940	18190	21440	23770	25260	25970
4.5	4060	9880	15680	20470	24120	26750	28410	29220
5.0	4511	10983	17421	22743	26795	29718	31569	32467
5.5	4960	12080	19160	25020	29470	32690	34730	35710
6.0	5410	13180	20910	27290	32150	35660	37880	38960
6.5	5860	14280	22650	29570	34830	38630	41040	42210
7.0	6320	15380	24390	31840	37510	41610	44200	45450
7.5	6770	16470	26130	34110	40190	44580	47350	48700
8.0	7220	17570	27870	36390	42870	47550	50510	51950
8.5	7670	18670	29620	38660	45550	50520	53670	55190
9.0	8120	19770	31360	40940	48230	53490	56820	58440
9.5	8570	20870	33100	43210	50910	56460	59980	61690
10.0	9020	21970	34840	45490	53590	59440	63140	64930

Table G9

Turbine Characteristics

Cut-in Velocity = 4 m/s
Rated Velocity = 10 m/s
Furling Velocity = 15 m/s

Turbine Rated Pwr (kW)	Average Wind Velocity (m/s) 3	4	5	6	7	8	9	10
0.5	300	780	1310	1790	2130	2330	2400	2370
1.0	610	1550	2620	3580	4260	4660	4800	4740
1.5	910	2330	3930	5360	6390	6990	7200	7120
2.0	1220	3100	5240	7150	8530	9320	9600	9490
2.5	1520	3880	6550	8940	10660	11650	12000	11860
3.0	1830	4660	7860	10730	12790	13980	14400	14230
3.5	2130	5430	9170	12510	14920	16310	16800	16600
4.0	2440	6210	10480	14300	17050	18640	19200	18970
4.5	2740	6980	11790	16090	19180	20970	21600	21350
5.0	3044	7760	13096	17878	21316	23302	23995	23718
5.5	3350	8540	14410	19670	23450	25630	26390	26090
6.0	3650	9310	15720	21450	25580	27960	28790	28460
6.5	3960	10090	17030	23240	27710	30290	31190	30830
7.0	4260	10860	18330	25030	29840	32620	33590	33200
7.5	4570	11640	19640	26820	31970	34950	35990	35580
8.0	4870	12420	20950	28600	34110	37280	38390	37950
8.5	5170	13190	22260	30390	36240	39610	40790	40320
9.0	5480	13970	23570	32180	38370	41940	43190	42690
9.5	5780	14740	24880	33970	40500	44270	45590	45060
10.0	6090	15520	26190	35760	42630	46600	47990	47440

Table G10

Turbine Characteristics

Cut-in Velocity = 4 m/s
Rated Velocity = 10 m/s
Furling Velocity = 20 m/s

Turbine Rated Pwr (kW)	Average Wind Velocity (m/s) 3	4	5	6	7	8	9	10
0.5	300	780	1310	1820	2240	2570	2800	2930
1.0	610	1550	2630	3640	4480	5140	5600	5860
1.5	910	2330	3940	5460	6720	7710	8390	8780
2.0	1220	3100	5260	7270	8960	10280	11190	11710
2.5	1520	3880	6570	9090	11210	12860	13990	14640
3.0	1830	4660	7880	10910	13450	15430	16790	17570
3.5	2130	5430	9200	12730	15690	18000	19590	20500
4.0	2440	6210	10510	14550	17930	20570	22380	23420
4.5	2740	6980	11830	16370	20170	23140	25180	26350
5.0	3044	7760	13140	18184	22411	25711	27981	29280
5.5	3350	8540	14450	20000	24650	28280	30780	32210
6.0	3650	9310	15770	21820	26890	30850	33580	35140
6.5	3960	10090	17080	23640	29130	33420	36380	38060
7.0	4260	10860	18400	25460	31380	35990	39170	40990
7.5	4570	11640	19710	27280	33620	38570	41970	43920
8.0	4870	12420	21020	29090	35860	41140	44770	46850
8.5	5170	13190	22340	30910	38100	43710	47570	49780
9.0	5480	13970	23650	32730	40340	46280	50370	52700
9.5	5780	14740	24970	34550	42580	48850	53160	55630
10.0	6090	15520	26280	36370	44820	51420	55960	58560

Table G11

Turbine Characteristics

Cut-in Velocity = 4 m/s
Rated Velocity = 12 m/s
Furling Velocity = 20 m/s

Turbine Rated Pwr (kW)	Average Wind Velocity (m/s) 3	4	5	6	7	8	9	10
0.5	230	590	1020	1460	1870	2200	2450	2610
1.0	460	1170	2040	2930	3730	4410	4900	5220
1.5	680	1760	3060	4390	5600	6610	7350	7830
2.0	910	2350	4080	5850	7460	8810	9800	10440
2.5	1140	2940	5100	7310	9330	11020	12260	13040
3.0	1370	3520	6120	8780	11190	13220	14710	15650
3.5	1600	4110	7140	10240	13060	15420	17160	18260
4.0	1830	4700	8160	11700	14920	17630	19610	20870
4.5	2050	5290	9180	13170	16790	19830	22060	23480
5.0	2283	5875	10205	14629	18653	22031	24512	26088
5.5	2510	6460	11230	16090	20520	24230	26960	28700
6.0	2740	7050	12250	17560	22380	26440	29410	31310
6.5	2970	7640	13270	19020	24250	28640	31870	33910
7.0	3200	8220	14290	20480	26110	30840	34320	36520
7.5	3420	8810	15310	21940	27980	33050	36770	39130
8.0	3650	9400	16330	23410	29850	35250	39220	41740
8.5	3880	9990	17350	24870	31710	37450	41670	44350
9.0	4110	10570	18370	26330	33580	39660	44120	46960
9.5	4340	11160	19390	27800	35440	41860	46570	49570
10.0	4570	11750	20410	29260	37310	44060	49020	52180

Table G12

Turbine Characteristics

Cut-in Velocity = 4 m/s
Rated Velocity = 12 m/s
Furling Velocity = 25 m/s

Turbine Rated Pwr (kW)	Average Wind Velocity (m/s) 3	4	5	6	7	8	9	10
0.5	230	590	1020	1460	1870	2230	2530	2760
1.0	460	1170	2040	2930	3750	4470	5060	5520
1.5	680	1760	3060	4390	5620	6700	7590	8290
2.0	910	2350	4080	5850	7500	8940	10120	11050
2.5	1140	2940	5100	7310	9370	11170	12650	13810
3.0	1370	3520	6120	8780	11240	13400	15180	16570
3.5	1600	4110	7140	10240	13120	15640	17710	19330
4.0	1830	4700	8160	11700	14990	17870	20240	22100
4.5	2050	5290	9180	13170	16870	20100	22770	24860
5.0	2283	5875	10205	14629	18741	22338	25300	27621
5.5	2510	6460	11230	16090	20620	24570	27830	30380
6.0	2740	7050	12250	17560	22490	26810	30360	33150
6.5	2970	7640	13270	19020	24360	29040	32890	35910
7.0	3200	8220	14290	20480	26240	31270	35420	38670
7.5	3420	8810	15310	21940	28110	33510	37950	41430
8.0	3650	9400	16330	23410	29990	35740	40480	44190
8.5	3880	9990	17350	24870	31860	37970	43010	46960
9.0	4110	10570	18370	26330	33730	40210	45540	49720
9.5	4340	11160	19390	27800	35610	42440	48070	52480
10.0	4570	11750	20410	29260	37480	44680	50600	55240

Table G13

Turbine Characteristics

Cut-in Velocity = 5 m/s
Rated Velocity = 9 m/s
Furling Velocity = 15 m/s

Turbine Rated Pwr (kW)	Average Wind Velocity (m/s) 3	4	5	6	7	8	9	10
0.5	190	650	1220	1740	2110	2330	2410	2390
1.0	370	1290	2440	3480	4230	4660	4820	4770
1.5	560	1940	3670	5220	6340	6990	7230	7160
2.0	750	2590	4890	6960	8450	9320	9640	9540
2.5	940	3240	6110	8710	10570	11650	12050	11930
3.0	1120	3880	7330	10450	12680	13970	14450	14320
3.5	1310	4530	8550	12190	14790	16300	16860	16700
4.0	1500	5180	9780	13930	16910	18630	19270	19090
4.5	1690	5820	11000	15670	19020	20960	21680	21470
5.0	1872	6471	12220	17411	21134	23291	24090	23860
5.5	2060	7120	13440	19150	23250	25620	26500	26250
6.0	2250	7770	14660	20890	25360	27950	28910	28630
6.5	2430	8410	15890	22630	27470	30280	31320	31020
7.0	2620	9060	17110	24370	29590	32610	33730	33400
7.5	2810	9710	18330	26120	31700	34940	36140	35790
8.0	3000	10350	19550	27860	33810	37270	38540	38180
8.5	3180	11000	20770	29600	35930	39590	40950	40560
9.0	3370	11650	22000	31340	38040	41920	43360	42950
9.5	3560	12300	23220	33080	40150	44250	45770	45330
10.0	3740	12940	24440	34820	42270	46580	48180	47720

Table G14

Turbine Characteristics

Cut-in Velocity = 5 m/s
Rated Velocity = 9 m/s
Furling Velocity = 20 m/s

Turbine Rated Pwr (kW)	Average Wind Velocity (m/s) 3	4	5	6	7	8	9	10
0.5	190	650	1230	1770	2220	2570	2810	2940
1.0	370	1290	2450	3540	4450	5140	5620	5880
1.5	560	1940	3680	5320	6670	7710	8420	8830
2.0	750	2590	4910	7090	8890	10280	11230	11770
2.5	940	3240	6130	8860	11110	12850	14040	14710
3.0	1120	3880	7360	10630	13340	15420	16850	17650
3.5	1310	4530	8580	12400	15560	17990	19650	20600
4.0	1500	5180	9810	14170	17780	20560	22460	23540
4.5	1690	5820	11040	15950	20010	23130	25270	26480
5.0	1872	6471	12264	17717	22229	25700	28076	29423
5.5	2060	7120	13490	19490	24450	28270	30880	32360
6.0	2250	7770	14720	21260	26670	30840	33690	35310
6.5	2430	8410	15940	23030	28900	33410	36500	38250
7.0	2620	9060	17170	24800	31120	35980	39310	41190
7.5	2810	9710	18400	26580	33340	38550	42110	44130
8.0	3000	10350	19620	28350	35570	41120	44920	47080
8.5	3180	11000	20850	30120	37790	43690	47730	50020
9.0	3370	11650	22080	31890	40010	46260	50540	52960
9.5	3560	12300	23300	33660	42230	48830	53340	55900
10.0	3740	12940	24530	35430	44460	51400	56150	58850

Table G15

Turbine Characteristics

Cut-in Velocity = 5 m/s
Rated Velocity = 11 m/s
Furling Velocity = 20 m/s

Turbine Rated Pwr (kW)	Average Wind Velocity (m/s) 3	4	5	6	7	8	9	10
0.5	130	450	900	1390	1820	2180	2450	2620
1.0	250	900	1810	2770	3640	4370	4900	5230
1.5	380	1350	2710	4160	5470	6550	7350	7850
2.0	500	1800	3620	5540	7290	8740	9800	10470
2.5	630	2250	4520	6930	9110	10920	12250	13080
3.0	750	2700	5430	8310	10930	13100	14690	15700
3.5	880	3150	6330	9700	12750	15290	17140	18310
4.0	1000	3600	7240	11080	14580	17470	19590	20930
4.5	1130	4050	8140	12470	16400	19660	22040	23550
5.0	1256	4497	9045	13855	18221	21842	24492	26163
5.5	1380	4950	9950	15240	20040	24030	26940	28780
6.0	1510	5400	10850	16630	21860	26210	29390	31400
6.5	1630	5850	11760	18010	23690	28390	31840	34010
7.0	1760	6300	12660	19400	25510	30580	34290	36630
7.5	1880	6750	13570	20780	27330	32760	36740	39240
8.0	2010	7190	14470	22170	29150	34950	39190	41860
8.5	2130	7640	15380	23550	30980	37130	41640	44480
9.0	2260	8090	16280	24940	32800	39310	44080	47090
9.5	2390	8540	17180	26330	34620	41500	46530	49710
10.0	2510	8990	18090	27710	36440	43680	48980	52330

Table G16

Turbine Characteristics

Cut-in Velocity = 5 m/s
Rated Velocity = 11 m/s
Furling Velocity = 25 m/s

Turbine Rated Pwr (kW)	Average Wind Velocity (m/s) 3	4	5	6	7	8	9	10
0.5	130	450	900	1390	1830	2210	2530	2770
1.0	250	900	1810	2770	3660	4430	5060	5540
1.5	380	1350	2710	4160	5490	6640	7580	8310
2.0	500	1800	3620	5540	7320	8860	10110	11080
2.5	630	2250	4520	6930	9150	11070	12640	13850
3.0	750	2700	5430	8310	10990	13290	15170	16620
3.5	880	3150	6330	9700	12820	15500	17700	19390
4.0	1000	3600	7240	11080	14650	17720	20220	22160
4.5	1130	4050	8140	12470	16480	19930	22750	24930
5.0	1256	4497	9045	13855	18308	22148	25280	27696
5.5	1380	4950	9950	15240	20140	24360	27810	30470
6.0	1510	5400	10850	16630	21970	26580	30340	33240
6.5	1630	5850	11760	18010	23800	28790	32860	36010
7.0	1760	6300	12660	19400	25630	31010	35390	38770
7.5	1880	6750	13570	20780	27460	33220	37920	41540
8.0	2010	7190	14470	22170	29290	35440	40450	44310
8.5	2130	7640	15380	23550	31120	37650	42980	47080
9.0	2260	8090	16280	24940	32960	39870	45500	49850
9.5	2390	8540	17180	26330	34790	42080	48030	52620
10.0	2510	8990	18090	27710	36620	44300	50560	55390

Table G17

Turbine Characteristics

Cut-in Velocity = 5 m/s
Rated Velocity = 13 m/s
Furling Velocity = 20 m/s

Turbine Rated Pwr (kW)	Average Wind Velocity (m/s) 3	4	5	6	7	8	9	10
0.5	90	340	700	1100	1500	1850	2120	2300
1.0	190	680	1390	2200	2990	3690	4230	4600
1.5	280	1020	2090	3300	4490	5540	6350	6910
2.0	380	1360	2790	4400	5980	7380	8470	9210
2.5	470	1700	3480	5500	7480	9230	10590	11510
3.0	570	2040	4180	6600	8970	11080	12700	13810
3.5	660	2380	4870	7700	10470	12920	14820	16120
4.0	750	2720	5570	8800	11970	14770	16940	18420
4.5	850	3060	6270	9900	13460	16620	19050	20720
5.0	942	3395	6964	11005	14958	18462	21172	23022
5.5	1040	3730	7660	12110	16450	20310	23290	25320
6.0	1130	4070	8360	13210	17950	22150	25410	27630
6.5	1220	4410	9050	14310	19450	24000	27520	29930
7.0	1320	4750	9750	15410	20940	25850	29640	32230
7.5	1410	5090	10450	16510	22440	27690	31760	34530
8.0	1510	5430	11140	17610	23930	29540	33870	36840
8.5	1600	5770	11840	18710	25430	31380	35990	39140
9.0	1700	6110	12540	19810	26920	33230	38110	41440
9.5	1790	6450	13230	20910	28420	35080	40230	43740
10.0	1880	6790	13930	22010	29920	36920	42340	46040

Table G18

Turbine Characteristics

Cut-in Velocity = 5 m/s
Rated Velocity = 13 m/s
Furling Velocity = 25 m/s

Turbine Rated Pwr (kW)	Average Wind Velocity (m/s) 3	4	5	6	7	8	9	10
0.5	90	340	700	1100	1500	1880	2200	2460
1.0	190	680	1390	2200	3010	3750	4390	4910
1.5	280	1020	2090	3300	4510	5630	6590	7370
2.0	380	1360	2790	4400	6020	7510	8780	9820
2.5	470	1700	3480	5500	7520	9380	10980	12280
3.0	570	2040	4180	6600	9030	11260	13180	14730
3.5	660	2380	4870	7700	10530	13140	15370	17190
4.0	750	2720	5570	8800	12040	15010	17570	19640
4.5	850	3060	6270	9900	13540	16890	19760	22100
5.0	942	3395	6964	11005	15045	18768	21960	24560
5.5	1040	3730	7660	12110	16550	20650	24160	27010
6.0	1130	4070	8360	13210	18050	22520	26350	29470
6.5	1220	4410	9050	14310	19560	24400	28550	31920
7.0	1320	4750	9750	15410	21060	26280	30740	34380
7.5	1410	5090	10450	16510	22570	28150	32940	36830
8.0	1510	5430	11140	17610	24070	30030	35140	39290
8.5	1600	5770	11840	18710	25580	31910	37330	41740
9.0	1700	6110	12540	19810	27080	33780	39530	44200
9.5	1790	6450	13230	20910	28590	35660	41720	46660
10.0	1880	6790	13930	22010	30090	37540	43920	49110

Table H1: Average Velocity = 5 m/s

	K = 1.5				K = 1.8				K = 2			
Wind V (m/s)	Prob Distbn	Distbn Density	Hours p.a	Power in wind (kWh/m2)	Prob Distbn	Distbn Density	Hours p.a	Power in wind (kWh/m2)	Prob Distbn	Distbn Density	Hours p.a	Power in wind (kWh/m2)
0.0	1.000	0.000	0.0	0.0	1.000	0.000	0.0	0.0	1.000	0.000	0.0	0.0
0.5	0.974	0.026	229.1	0.0	0.987	0.013	111.6	0.0	0.992	0.008	68.9	0.0
1.0	0.928	0.046	403.5	0.3	0.956	0.031	270.9	0.2	0.969	0.023	203.6	0.1
1.5	0.871	0.056	494.3	1.1	0.912	0.045	392.5	0.9	0.931	0.038	328.8	0.7
2.0	0.809	0.062	546.6	2.8	0.856	0.056	486.3	2.5	0.881	0.050	439.0	2.3
2.5	0.744	0.065	572.8	5.8	0.793	0.063	554.7	5.6	0.821	0.060	529.9	5.4
3.0	0.677	0.066	579.6	10.2	0.724	0.068	599.2	10.5	0.752	0.068	598.5	10.5
3.5	0.612	0.065	571.8	15.9	0.653	0.071	621.8	17.3	0.679	0.073	643.4	17.9
4.0	0.549	0.063	553.0	23.0	0.582	0.071	625.1	26.0	0.603	0.076	664.8	27.7
4.5	0.489	0.060	526.2	31.2	0.512	0.070	611.8	36.2	0.527	0.076	664.0	39.3
5.0	0.433	0.056	493.8	40.1	0.445	0.067	585.1	47.5	0.454	0.074	643.9	52.3
5.5	0.380	0.052	457.9	49.5	0.383	0.063	548.1	59.3	0.384	0.069	607.8	65.7
6.0	0.332	0.048	420.1	59.0	0.325	0.058	503.8	70.7	0.321	0.064	559.6	78.6
6.5	0.289	0.044	381.7	68.1	0.273	0.052	455.2	81.2	0.263	0.057	503.3	89.8
7.0	0.250	0.039	343.7	76.6	0.227	0.046	404.6	90.2	0.213	0.051	442.7	98.7
7.5	0.214	0.035	307.0	84.2	0.187	0.040	354.1	97.1	0.169	0.044	381.3	104.5
8.0	0.183	0.031	272.2	90.6	0.152	0.035	305.4	101.6	0.132	0.037	321.6	107.0
8.5	0.156	0.027	239.5	95.6	0.122	0.030	259.8	103.7	0.102	0.030	266.0	106.2
9.0	0.132	0.024	209.4	99.2	0.097	0.025	218.0	103.3	0.077	0.025	215.7	102.2
9.5	0.111	0.021	181.9	101.4	0.077	0.021	180.6	100.6	0.058	0.020	171.7	95.7
10.0	0.093	0.018	157.1	102.1	0.060	0.017	147.7	96.0	0.042	0.015	134.1	87.1
10.5	0.078	0.015	134.8	101.5	0.046	0.014	119.3	89.8	0.031	0.012	102.8	77.3
11.0	0.065	0.013	115.1	99.6	0.035	0.011	95.3	82.4	0.022	0.009	77.4	67.0
11.5	0.054	0.011	97.7	96.6	0.027	0.009	75.2	74.3	0.015	0.007	57.2	56.6
12.0	0.044	0.009	82.5	92.7	0.020	0.007	58.6	65.8	0.011	0.005	41.6	46.7
12.5	0.036	0.008	69.4	88.1	0.015	0.005	45.2	57.4	0.007	0.003	29.7	37.7
13.0	0.030	0.007	58.0	82.9	0.011	0.004	34.5	49.3	0.005	0.002	20.8	29.7
13.5	0.024	0.006	48.3	77.2	0.008	0.003	26.0	41.6	0.003	0.002	14.4	23.0
14.0	0.020	0.005	40.0	71.4	0.006	0.002	19.4	34.6	0.002	0.001	9.7	17.4
14.5	0.016	0.004	33.0	65.4	0.004	0.002	14.3	28.4	0.001	0.001	6.5	12.8
15.0	0.013	0.003	27.1	59.5	0.003	0.001	10.5	23.0	0.001	0.000	4.2	9.3
15.5	0.010	0.003	22.2	53.7	0.002	0.001	7.6	18.4	0.001	0.000	2.7	6.6
16.0	0.008	0.002	18.1	48.1	0.001	0.001	5.4	14.5	0.000	0.000	1.7	4.6
16.5	0.007	0.002	14.7	42.8	0.001	0.000	3.9	11.2	0.000	0.000	1.1	3.1
17.0	0.005	0.001	11.8	37.8	0.001	0.000	2.7	8.6	0.000	0.000	0.7	2.1
17.5	0.004	0.001	9.5	33.2	0.000	0.000	1.9	6.5	0.000	0.000	0.4	1.4
18.0	0.003	0.001	7.6	29.0	0.000	0.000	1.3	4.9	0.000	0.000	0.2	0.9
18.5	0.003	0.001	6.1	25.1	0.000	0.000	0.9	3.6	0.000	0.000	0.1	0.6
19.0	0.002	0.001	4.9	21.7	0.000	0.000	0.6	2.7	0.000	0.000	0.1	0.4
19.5	0.002	0.000	3.9	18.6	0.000	0.000	0.4	1.9	0.000	0.000	0.0	0.2
20.0	0.001	0.000	3.0	15.8	0.000	0.000	0.3	1.4	0.000	0.000	0.0	0.1
20.5	0.001	0.000	2.4	13.4	0.000	0.000	0.2	1.0	0.000	0.000	0.0	0.1
21.0	0.001	0.000	1.9	11.3	0.000	0.000	0.1	0.7	0.000	0.000	0.0	0.0
21.5	0.001	0.000	1.5	9.5	0.000	0.000	0.1	0.5	0.000	0.000	0.0	0.0
22.0	0.000	0.000	1.1	7.9	0.000	0.000	0.0	0.3	0.000	0.000	0.0	0.0
22.5	0.000	0.000	0.9	6.6	0.000	0.000	0.0	0.2	0.000	0.000	0.0	0.0
23.0	0.000	0.000	0.7	5.5	0.000	0.000	0.0	0.1	0.000	0.000	0.0	0.0
23.5	0.000	0.000	0.5	4.5	0.000	0.000	0.0	0.1	0.000	0.000	0.0	0.0
24.0	0.000	0.000	0.4	3.7	0.000	0.000	0.0	0.1	0.000	0.000	0.0	0.0
24.5	0.000	0.000	0.3	3.0	0.000	0.000	0.0	0.0	0.000	0.000	0.0	0.0
25.0	0.000	0.000	0.2	2.4	0.000	0.000	0.0	0.0	0.000	0.000	0.0	0.0

Table H2: Average Velocity = 6 m/s

Wind V (m/s)	K = 1.5 Prob Distbn	K = 1.5 Distbn Density	K = 1.5 Hours p.a	K = 1.5 Power in wind (kWh/m2)	K = 1.8 Prob Distbn	K = 1.8 Distbn Density	K = 1.8 Hours p.a	K = 1.8 Power in wind (kWh/m2)	K = 2 Prob Distbn	K = 2 Distbn Density	K = 2 Hours p.a	K = 2 Power in wind (kWh/m2)
0.0	1.000	0.000	0.0	0.0	1.000	0.000	0.0	0.0	1.000	0.000	0.0	0.0
0.5	0.980	0.020	174.8	0.0	0.991	0.009	80.5	0.0	0.995	0.005	47.9	0.0
1.0	0.945	0.035	310.7	0.2	0.968	0.022	196.7	0.1	0.978	0.016	142.2	0.1
1.5	0.901	0.044	385.7	0.8	0.935	0.033	288.1	0.6	0.952	0.026	231.9	0.5
2.0	0.851	0.049	433.6	2.3	0.894	0.041	362.6	1.9	0.916	0.036	314.2	1.6
2.5	0.798	0.053	463.0	4.7	0.846	0.048	421.7	4.3	0.872	0.044	386.6	3.9
3.0	0.744	0.055	478.6	8.4	0.793	0.053	466.3	8.2	0.821	0.051	447.3	7.9
3.5	0.688	0.055	483.2	13.5	0.736	0.057	497.2	13.9	0.764	0.057	495.0	13.8
4.0	0.634	0.055	479.2	19.9	0.677	0.059	515.3	21.4	0.704	0.060	528.9	22.0
4.5	0.580	0.053	468.4	27.7	0.618	0.060	521.8	30.9	0.641	0.063	549.1	32.5
5.0	0.529	0.052	452.3	36.7	0.558	0.059	518.0	42.1	0.578	0.063	556.1	45.2
5.5	0.479	0.049	432.2	46.7	0.501	0.058	505.4	54.7	0.515	0.063	550.8	59.6
6.0	0.433	0.047	409.2	57.4	0.445	0.055	485.4	68.2	0.454	0.061	534.7	75.1
6.5	0.389	0.044	384.2	68.6	0.393	0.052	459.6	82.0	0.396	0.058	509.5	91.0
7.0	0.348	0.041	358.0	79.8	0.344	0.049	429.6	95.8	0.341	0.054	477.2	106.4
7.5	0.310	0.038	331.4	90.9	0.299	0.045	396.5	108.7	0.291	0.050	439.6	120.6
8.0	0.275	0.035	304.8	101.4	0.257	0.041	361.8	120.4	0.245	0.046	398.7	132.7
8.5	0.243	0.032	278.7	111.2	0.220	0.037	326.5	130.4	0.205	0.041	356.1	142.2
9.0	0.214	0.029	253.3	120.0	0.187	0.033	291.6	138.2	0.169	0.036	313.5	148.5
9.5	0.188	0.026	229.1	127.7	0.157	0.029	257.8	143.7	0.138	0.031	272.0	151.6
10.0	0.165	0.024	206.2	134.0	0.131	0.026	225.7	146.7	0.111	0.027	232.8	151.3
10.5	0.144	0.021	184.7	139.0	0.109	0.022	195.7	147.3	0.089	0.022	196.6	147.9
11.0	0.125	0.019	164.7	142.5	0.090	0.019	168.2	145.5	0.070	0.019	163.8	141.7
11.5	0.108	0.017	146.2	144.5	0.074	0.016	143.2	141.6	0.055	0.015	134.6	133.1
12.0	0.093	0.015	129.2	145.2	0.060	0.014	120.9	135.8	0.042	0.012	109.3	122.7
12.5	0.080	0.013	113.8	144.5	0.048	0.012	101.2	128.5	0.032	0.010	87.6	111.2
13.0	0.069	0.011	99.8	142.5	0.039	0.010	84.0	120.0	0.024	0.008	69.3	99.0
13.5	0.059	0.010	87.2	139.5	0.031	0.008	69.2	110.7	0.018	0.006	54.2	86.6
14.0	0.050	0.009	75.9	135.4	0.024	0.006	56.5	100.8	0.014	0.005	41.8	74.5
14.5	0.043	0.008	65.9	130.5	0.019	0.005	45.8	90.8	0.010	0.004	31.9	63.1
15.0	0.036	0.007	56.9	124.9	0.015	0.004	36.8	80.8	0.007	0.003	24.0	52.7
15.5	0.031	0.006	49.1	118.8	0.012	0.003	29.4	71.1	0.005	0.002	17.9	43.2
16.0	0.026	0.005	42.1	112.2	0.009	0.003	23.3	62.0	0.004	0.001	13.1	35.0
16.5	0.022	0.004	36.1	105.3	0.007	0.002	18.3	53.4	0.003	0.001	9.5	27.8
17.0	0.018	0.004	30.8	98.3	0.005	0.002	14.3	45.6	0.002	0.001	6.8	21.9
17.5	0.015	0.003	26.2	91.2	0.004	0.001	11.1	38.5	0.001	0.001	4.9	16.9
18.0	0.013	0.003	22.2	84.2	0.003	0.001	8.5	32.2	0.001	0.000	3.4	12.9
18.5	0.011	0.002	18.8	77.3	0.002	0.001	6.5	26.7	0.001	0.000	2.4	9.7
19.0	0.009	0.002	15.8	70.7	0.002	0.001	4.9	21.9	0.000	0.000	1.6	7.2
19.5	0.007	0.002	13.3	64.2	0.001	0.000	3.7	17.9	0.000	0.000	1.1	5.3
20.0	0.006	0.001	11.2	58.1	0.001	0.000	2.8	14.4	0.000	0.000	0.7	3.8
20.5	0.005	0.001	9.3	52.3	0.001	0.000	2.1	11.5	0.000	0.000	0.5	2.7
21.0	0.004	0.001	7.8	46.9	0.000	0.000	1.5	9.1	0.000	0.000	0.3	1.9
21.5	0.003	0.001	6.5	41.9	0.000	0.000	1.1	7.2	0.000	0.000	0.2	1.3
22.0	0.003	0.001	5.4	37.2	0.000	0.000	0.8	5.6	0.000	0.000	0.1	0.9
22.5	0.002	0.001	4.5	33.0	0.000	0.000	0.6	4.3	0.000	0.000	0.1	0.6
23.0	0.002	0.000	3.7	29.1	0.000	0.000	0.4	3.3	0.000	0.000	0.1	0.4
23.5	0.002	0.000	3.0	25.5	0.000	0.000	0.3	2.5	0.000	0.000	0.0	0.3
24.0	0.001	0.000	2.5	22.4	0.000	0.000	0.2	1.9	0.000	0.000	0.0	0.2
24.5	0.001	0.000	2.0	19.5	0.000	0.000	0.1	1.4	0.000	0.000	0.0	0.1
25.0	0.001	0.000	1.7	16.9	0.000	0.000	0.1	1.1	0.000	0.000	0.0	0.1

Table H3: Average Velocity = 7 m/s

	K = 1.5				K = 1.8				K = 2			
Wind V (m/s)	Prob Distbn	Distbn Density	Hours p.a	Power in wind (kWh/m2)	Prob Distbn	Distbn Density	Hours p.a	Power in wind (kWh/m2)	Prob Distbn	Distbn Density	Hours p.a	Power in wind (kWh/m2)
0.0	1.000	0.000	0.0	0.0	1.000	0.000	0.0	0.0	1.000	0.000	0.0	0.0
0.5	0.984	0.016	139.0	0.0	0.993	0.007	61.1	0.0	0.996	0.004	35.2	0.0
1.0	0.956	0.028	248.5	0.2	0.976	0.017	149.8	0.1	0.984	0.012	104.9	0.1
1.5	0.920	0.036	311.2	0.7	0.951	0.025	221.0	0.5	0.964	0.020	172.0	0.4
2.0	0.880	0.040	353.6	1.8	0.919	0.032	280.7	1.5	0.938	0.027	235.1	1.2
2.5	0.836	0.044	382.4	3.9	0.881	0.038	330.5	3.4	0.904	0.033	292.6	3.0
3.0	0.790	0.046	400.7	7.0	0.839	0.042	370.8	6.5	0.865	0.039	343.5	6.0
3.5	0.744	0.047	410.9	11.5	0.793	0.046	402.1	11.2	0.821	0.044	386.8	10.8
4.0	0.696	0.047	414.2	17.2	0.744	0.048	424.8	17.7	0.773	0.048	421.9	17.5
4.5	0.649	0.047	412.1	24.4	0.694	0.050	439.3	26.0	0.721	0.051	448.3	26.6
5.0	0.603	0.046	405.4	32.9	0.643	0.051	446.4	36.3	0.668	0.053	466.0	37.9
5.5	0.558	0.045	395.1	42.7	0.592	0.051	446.7	48.3	0.614	0.054	475.2	51.4
6.0	0.514	0.044	381.9	53.6	0.542	0.050	441.0	61.9	0.560	0.054	476.3	66.9
6.5	0.472	0.042	366.4	65.4	0.493	0.049	430.1	76.8	0.506	0.054	470.0	83.9
7.0	0.433	0.040	349.3	77.9	0.445	0.047	414.7	92.5	0.454	0.052	457.1	101.9
7.5	0.395	0.038	330.9	90.7	0.400	0.045	395.7	108.5	0.404	0.050	438.6	120.3
8.0	0.359	0.036	311.8	103.8	0.357	0.043	374.0	124.5	0.356	0.047	415.5	138.3
8.5	0.326	0.033	292.2	116.7	0.317	0.040	350.2	139.8	0.312	0.044	388.8	155.2
9.0	0.295	0.031	272.6	129.2	0.280	0.037	325.1	154.1	0.271	0.041	359.6	170.4
9.5	0.266	0.029	253.2	141.1	0.246	0.034	299.4	166.8	0.233	0.038	328.8	183.2
10.0	0.239	0.027	234.1	152.2	0.215	0.031	273.4	177.7	0.199	0.034	297.4	193.3
10.5	0.214	0.025	215.6	162.3	0.187	0.028	247.8	186.5	0.169	0.030	266.1	200.2
11.0	0.192	0.023	197.8	171.2	0.161	0.025	223.0	192.9	0.142	0.027	235.6	203.9
11.5	0.171	0.021	180.8	178.8	0.138	0.023	199.2	196.9	0.119	0.024	206.5	204.2
12.0	0.152	0.019	164.7	185.0	0.118	0.020	176.7	198.4	0.098	0.020	179.2	201.3
12.5	0.135	0.017	149.6	189.9	0.101	0.018	155.7	197.6	0.080	0.018	154.0	195.5
13.0	0.120	0.015	135.3	193.3	0.085	0.016	136.2	194.6	0.066	0.015	131.0	187.1
13.5	0.106	0.014	122.1	195.2	0.071	0.014	118.5	189.4	0.053	0.013	110.4	176.6
14.0	0.093	0.013	109.8	195.8	0.060	0.012	102.3	182.5	0.042	0.011	92.2	164.5
14.5	0.082	0.011	98.4	195.1	0.050	0.010	87.9	174.1	0.034	0.009	76.3	151.1
15.0	0.072	0.010	88.0	193.1	0.041	0.009	75.0	164.5	0.027	0.007	62.5	137.1
15.5	0.063	0.009	78.5	189.9	0.034	0.007	63.6	154.0	0.021	0.006	50.7	122.8
16.0	0.055	0.008	69.8	185.8	0.028	0.006	53.6	142.8	0.016	0.005	40.8	108.7
16.5	0.048	0.007	61.9	180.7	0.023	0.005	45.0	131.3	0.012	0.004	32.5	95.0
17.0	0.042	0.006	54.7	174.8	0.018	0.004	37.5	119.7	0.009	0.003	25.7	82.1
17.5	0.036	0.006	48.3	168.2	0.015	0.004	31.1	108.2	0.007	0.002	20.1	70.1
18.0	0.032	0.005	42.5	161.1	0.012	0.003	25.6	97.0	0.005	0.002	15.6	59.2
18.5	0.027	0.004	37.3	153.6	0.010	0.002	21.0	86.3	0.004	0.001	12.0	49.5
19.0	0.024	0.004	32.7	145.7	0.008	0.002	17.1	76.2	0.003	0.001	9.2	40.9
19.5	0.020	0.003	28.6	137.7	0.006	0.002	13.9	66.8	0.002	0.001	6.9	33.4
20.0	0.017	0.003	24.9	129.5	0.005	0.001	11.2	58.1	0.002	0.001	5.2	27.0
20.5	0.015	0.002	21.7	121.4	0.004	0.001	9.0	50.1	0.001	0.000	3.9	21.6
21.0	0.013	0.002	18.8	113.3	0.003	0.001	7.1	43.0	0.001	0.000	2.8	17.1
21.5	0.011	0.002	16.3	105.3	0.002	0.001	5.7	36.6	0.001	0.000	2.1	13.4
22.0	0.009	0.002	14.1	97.5	0.002	0.001	4.5	31.0	0.000	0.000	1.5	10.4
22.5	0.008	0.001	12.2	90.0	0.001	0.000	3.5	26.0	0.000	0.000	1.1	8.0
23.0	0.007	0.001	10.5	82.7	0.001	0.000	2.7	21.7	0.000	0.000	0.8	6.1
23.5	0.006	0.001	9.0	75.8	0.001	0.000	2.1	18.0	0.000	0.000	0.5	4.6
24.0	0.005	0.001	7.7	69.2	0.001	0.000	1.7	14.8	0.000	0.000	0.4	3.4
24.5	0.004	0.001	6.6	63.0	0.000	0.000	1.3	12.1	0.000	0.000	0.3	2.5
25.0	0.003	0.001	5.6	57.2	0.000	0.000	1.0	9.9	0.000	0.000	0.2	1.8

Table H4: Average Velocity = 8 m/s

	K = 1.5				K = 1.8				K = 2			
Wind V (m/s)	Prob Distbn	Distbn Density	Hours p.a	Power in wind (kWh/m2)	Prob Distbn	Distbn Density	Hours p.a	Power in wind (kWh/m2)	Prob Distbn	Distbn Density	Hours p.a	Power in wind (kWh/m2)
0.0	1.000	0.000	0.0	0.0	1.000	0.000	0.0	0.0	1.000	0.000	0.0	0.0
0.5	0.987	0.013	114.0	0.0	0.995	0.005	48.1	0.0	0.997	0.003	27.0	0.0
1.0	0.964	0.023	204.5	0.1	0.981	0.013	118.2	0.1	0.988	0.009	80.5	0.1
1.5	0.934	0.029	257.7	0.6	0.961	0.020	175.1	0.4	0.973	0.015	132.5	0.3
2.0	0.901	0.034	295.0	1.5	0.935	0.026	224.0	1.2	0.952	0.021	182.1	0.9
2.5	0.864	0.037	321.8	3.3	0.905	0.030	265.8	2.7	0.926	0.026	228.4	2.3
3.0	0.825	0.039	340.5	6.0	0.871	0.034	301.2	5.3	0.895	0.031	270.7	4.8
3.5	0.785	0.040	352.9	9.8	0.833	0.038	330.3	9.2	0.860	0.035	308.3	8.6
4.0	0.744	0.041	359.9	15.0	0.793	0.040	353.4	14.7	0.821	0.039	340.7	14.2
4.5	0.702	0.041	362.5	21.5	0.750	0.042	370.7	22.0	0.779	0.042	367.5	21.8
5.0	0.661	0.041	361.3	29.4	0.707	0.044	382.6	31.1	0.734	0.044	388.6	31.6
5.5	0.620	0.041	357.0	38.6	0.662	0.044	389.4	42.1	0.688	0.046	403.8	43.7
6.0	0.580	0.040	350.1	49.1	0.618	0.045	391.5	55.0	0.641	0.047	413.2	58.0
6.5	0.541	0.039	341.0	60.9	0.573	0.044	389.4	69.5	0.594	0.048	417.1	74.5
7.0	0.504	0.038	330.1	73.6	0.529	0.044	383.4	85.5	0.546	0.047	415.7	92.7
7.5	0.467	0.036	317.9	87.2	0.487	0.043	374.1	102.6	0.499	0.047	409.6	112.3
8.0	0.433	0.035	304.6	101.4	0.445	0.041	361.9	120.4	0.454	0.046	399.1	132.8
8.5	0.399	0.033	290.6	116.0	0.406	0.040	347.4	138.7	0.410	0.044	384.9	153.7
9.0	0.368	0.032	276.0	130.8	0.368	0.038	331.0	156.8	0.368	0.042	367.6	174.2
9.5	0.338	0.030	261.1	145.5	0.332	0.036	313.1	174.5	0.328	0.040	347.8	193.8
10.0	0.310	0.028	246.0	159.9	0.299	0.034	294.2	191.2	0.291	0.037	326.0	211.9
10.5	0.284	0.026	231.1	173.9	0.267	0.031	274.7	206.7	0.256	0.035	303.0	228.0
11.0	0.259	0.025	216.3	187.1	0.238	0.029	254.8	220.5	0.225	0.032	279.1	241.5
11.5	0.236	0.023	201.8	199.5	0.211	0.027	235.0	232.3	0.195	0.029	255.0	252.1
12.0	0.214	0.021	187.7	210.8	0.187	0.025	215.5	242.0	0.169	0.026	231.1	259.6
12.5	0.195	0.020	174.1	221.0	0.164	0.022	196.4	249.4	0.145	0.024	207.8	263.3
13.0	0.176	0.018	161.0	229.9	0.144	0.020	178.1	254.3	0.124	0.021	185.4	264.7
13.5	0.159	0.017	148.5	237.4	0.126	0.018	160.6	256.8	0.105	0.019	164.1	262.4
14.0	0.144	0.016	136.6	243.6	0.109	0.016	144.1	257.0	0.089	0.016	144.2	257.1
14.5	0.129	0.014	125.3	248.3	0.094	0.015	128.6	254.8	0.075	0.014	125.7	249.1
15.0	0.116	0.013	114.7	251.6	0.081	0.013	114.2	250.5	0.062	0.012	108.8	238.7
15.5	0.104	0.012	104.7	253.5	0.070	0.012	100.9	244.2	0.052	0.011	93.5	226.1
16.0	0.093	0.011	95.4	254.0	0.060	0.010	88.7	236.2	0.042	0.009	79.7	212.3
16.5	0.084	0.010	86.7	253.2	0.051	0.009	77.6	226.7	0.035	0.008	67.5	197.2
17.0	0.075	0.009	78.6	251.2	0.043	0.008	67.6	215.9	0.028	0.006	56.8	181.3
17.5	0.066	0.008	71.2	248.0	0.037	0.007	58.6	204.2	0.023	0.005	47.4	165.2
18.0	0.059	0.007	64.3	243.7	0.031	0.006	50.6	191.8	0.018	0.004	39.3	149.0
18.5	0.052	0.007	57.9	238.4	0.026	0.005	43.5	178.9	0.015	0.004	32.4	133.2
19.0	0.047	0.006	52.1	232.3	0.022	0.004	37.2	165.7	0.012	0.003	26.5	118.0
19.5	0.041	0.005	46.8	225.5	0.018	0.004	31.7	152.6	0.009	0.002	21.5	103.6
20.0	0.036	0.005	41.9	218.0	0.015	0.003	26.8	139.6	0.007	0.002	17.3	90.1
20.5	0.032	0.004	37.5	209.9	0.012	0.003	22.7	126.9	0.006	0.002	13.9	77.8
21.0	0.028	0.004	33.5	201.4	0.010	0.002	19.0	114.7	0.004	0.001	11.0	66.5
21.5	0.025	0.003	29.8	192.6	0.008	0.002	15.9	103.0	0.003	0.001	8.7	56.4
22.0	0.022	0.003	26.5	183.5	0.007	0.002	13.3	92.0	0.003	0.001	6.9	47.4
22.5	0.019	0.003	23.5	174.3	0.005	0.001	11.0	81.7	0.002	0.001	5.3	39.6
23.0	0.017	0.002	20.9	165.1	0.004	0.001	9.1	72.1	0.001	0.000	4.1	32.7
23.5	0.015	0.002	18.5	155.8	0.004	0.001	7.5	63.4	0.001	0.000	3.2	26.9
24.0	0.013	0.002	16.3	146.6	0.003	0.001	6.2	55.3	0.001	0.000	2.4	21.9
24.5	0.011	0.002	14.4	137.5	0.002	0.001	5.0	48.1	0.001	0.000	1.8	17.7
25.0	0.010	0.001	12.7	128.7	0.002	0.000	4.1	41.6	0.000	0.000	1.4	14.2

Table H5: Average Velocity = 9 m/s

Wind V (m/s)	K = 1.5 Prob Distbn	Distbn Density	Hours p.a	Power in wind (kWh/m2)	K = 1.8 Prob Distbn	Distbn Density	Hours p.a	Power in wind (kWh/m2)	K = 2 Prob Distbn	Distbn Density	Hours p.a	Power in wind (kWh/m2)
0.0	1.000	0.000	0.0	0.0	1.000	0.000	0.0	0.0	1.000	0.000	0.0	0.0
0.5	0.989	0.011	95.6	0.0	0.996	0.004	38.9	0.0	0.998	0.002	21.3	0.0
1.0	0.969	0.020	172.1	0.1	0.985	0.011	95.8	0.1	0.990	0.007	63.7	0.0
1.5	0.945	0.025	217.8	0.5	0.968	0.016	142.5	0.3	0.978	0.012	105.1	0.2
2.0	0.916	0.029	250.7	1.3	0.947	0.021	183.0	1.0	0.962	0.017	145.1	0.8
2.5	0.885	0.031	275.2	2.8	0.923	0.025	218.5	2.2	0.941	0.021	182.9	1.9
3.0	0.851	0.033	293.3	5.1	0.894	0.028	249.2	4.4	0.916	0.025	218.2	3.8
3.5	0.816	0.035	306.3	8.5	0.863	0.031	275.5	7.7	0.887	0.029	250.4	7.0
4.0	0.780	0.036	315.1	13.1	0.829	0.034	297.4	12.4	0.855	0.032	279.2	11.6
4.5	0.744	0.037	320.2	19.0	0.793	0.036	315.1	18.7	0.821	0.035	304.3	18.0
5.0	0.707	0.037	322.2	26.2	0.755	0.038	328.8	26.7	0.784	0.037	325.5	26.4
5.5	0.670	0.037	321.6	34.8	0.716	0.039	338.7	36.6	0.744	0.039	342.7	37.1
6.0	0.634	0.036	318.7	44.7	0.677	0.039	344.9	48.4	0.704	0.041	355.7	49.9
6.5	0.598	0.036	313.8	56.0	0.637	0.040	347.8	62.1	0.662	0.042	364.7	65.1
7.0	0.563	0.035	307.4	68.5	0.598	0.040	347.5	77.5	0.620	0.042	369.7	82.4
7.5	0.529	0.034	299.5	82.1	0.558	0.039	344.4	94.5	0.578	0.042	370.9	101.7
8.0	0.495	0.033	290.6	96.7	0.520	0.039	338.8	112.8	0.536	0.042	368.5	122.6
8.5	0.463	0.032	280.7	112.0	0.482	0.038	330.9	132.1	0.494	0.041	362.8	144.8
9.0	0.433	0.031	270.1	128.0	0.445	0.037	321.1	152.1	0.454	0.040	354.2	167.8
9.5	0.403	0.030	259.0	144.3	0.410	0.035	309.6	172.5	0.415	0.039	343.0	191.1
10.0	0.375	0.028	247.5	160.9	0.376	0.034	296.8	192.9	0.377	0.038	329.5	214.2
10.5	0.348	0.027	235.8	177.4	0.344	0.032	282.9	212.8	0.341	0.036	314.2	236.5
11.0	0.322	0.026	223.9	193.7	0.313	0.031	268.2	232.0	0.307	0.034	297.5	257.4
11.5	0.298	0.024	212.0	209.6	0.284	0.029	252.9	250.0	0.275	0.032	279.7	276.5
12.0	0.275	0.023	200.2	224.9	0.257	0.027	237.3	266.6	0.245	0.030	261.1	293.3
12.5	0.254	0.022	188.6	239.5	0.232	0.025	221.6	281.3	0.218	0.028	242.2	307.4
13.0	0.233	0.020	177.2	253.1	0.208	0.024	206.0	294.1	0.192	0.025	223.1	318.6
13.5	0.214	0.019	166.1	265.7	0.187	0.022	190.6	304.8	0.169	0.023	204.3	326.7
14.0	0.197	0.018	155.4	277.1	0.167	0.020	175.5	313.1	0.148	0.021	185.8	331.5
14.5	0.180	0.017	145.0	287.3	0.148	0.018	161.0	319.0	0.129	0.019	168.0	333.0
15.0	0.165	0.015	135.0	296.1	0.131	0.017	147.0	322.5	0.111	0.017	151.0	331.2
15.5	0.150	0.014	125.4	303.6	0.116	0.015	133.7	323.5	0.096	0.015	134.9	326.4
16.0	0.137	0.013	116.3	309.7	0.102	0.014	121.1	322.3	0.082	0.014	119.7	318.8
16.5	0.125	0.012	107.6	314.3	0.090	0.012	109.2	318.8	0.070	0.012	105.7	308.6
17.0	0.114	0.011	99.4	317.5	0.079	0.011	98.1	313.3	0.060	0.011	92.8	296.2
17.5	0.103	0.010	91.7	319.3	0.069	0.010	87.8	305.8	0.050	0.009	80.9	282.0
18.0	0.093	0.010	84.4	319.8	0.060	0.009	78.3	296.7	0.042	0.008	70.2	266.2
18.5	0.085	0.009	77.5	318.9	0.052	0.008	69.5	286.1	0.035	0.007	60.6	249.3
19.0	0.076	0.008	71.1	316.8	0.045	0.007	61.5	274.3	0.030	0.006	52.0	231.7
19.5	0.069	0.007	65.1	313.5	0.039	0.006	54.2	261.4	0.024	0.005	44.3	213.6
20.0	0.062	0.007	59.5	309.2	0.033	0.005	47.6	247.7	0.020	0.004	37.6	195.5
20.5	0.056	0.006	54.3	303.8	0.028	0.005	41.7	233.5	0.017	0.004	31.7	177.7
21.0	0.050	0.006	49.4	297.5	0.024	0.004	36.4	218.9	0.014	0.003	26.6	160.2
21.5	0.045	0.005	45.0	290.4	0.021	0.004	31.6	204.2	0.011	0.003	22.2	143.5
22.0	0.041	0.005	40.8	282.6	0.018	0.003	27.4	189.5	0.009	0.002	18.4	127.6
22.5	0.036	0.004	37.0	274.1	0.015	0.003	23.6	175.0	0.007	0.002	15.2	112.7
23.0	0.033	0.004	33.5	265.1	0.013	0.002	20.3	160.8	0.006	0.001	12.5	98.8
23.5	0.029	0.003	30.3	255.7	0.011	0.002	17.4	147.0	0.005	0.001	10.2	86.1
24.0	0.026	0.003	27.4	245.9	0.009	0.002	14.9	133.8	0.004	0.001	8.3	74.5
24.5	0.023	0.003	24.7	235.9	0.007	0.001	12.7	121.2	0.003	0.001	6.7	64.0
25.0	0.021	0.003	22.2	225.6	0.006	0.001	10.8	109.4	0.002	0.001	5.4	54.7

Table H6: Average Velocity = 10 m/s

Wind V (m/s)	K = 1.5 Prob Distbn	K = 1.5 Distbn Density	K = 1.5 Hours p.a	K = 1.5 Power in wind (kWh/m2)	K = 1.8 Prob Distbn	K = 1.8 Distbn Density	K = 1.8 Hours p.a	K = 1.8 Power in wind (kWh/m2)	K = 2 Prob Distbn	K = 2 Distbn Density	K = 2 Hours p.a	K = 2 Power in wind (kWh/m2)
0.0	1.000	0.000	0.0	0.0	1.000	0.000	0.0	0.0	1.000	0.000	0.0	0.0
0.5	0.991	0.009	81.7	0.0	0.996	0.004	32.2	0.0	0.998	0.002	17.3	0.0
1.0	0.974	0.017	147.4	0.1	0.987	0.009	79.4	0.1	0.992	0.006	51.7	0.0
1.5	0.952	0.021	187.2	0.4	0.974	0.014	118.4	0.3	0.982	0.010	85.4	0.2
2.0	0.928	0.025	216.3	1.1	0.956	0.017	152.5	0.8	0.969	0.013	118.2	0.6
2.5	0.901	0.027	238.6	2.4	0.935	0.021	182.9	1.9	0.952	0.017	149.6	1.5
3.0	0.871	0.029	255.7	4.5	0.912	0.024	209.6	3.7	0.931	0.020	179.2	3.1
3.5	0.841	0.031	268.6	7.5	0.885	0.027	233.1	6.5	0.908	0.024	206.8	5.8
4.0	0.809	0.032	278.0	11.6	0.856	0.029	253.3	10.5	0.881	0.027	232.2	9.7
4.5	0.776	0.032	284.5	16.8	0.825	0.031	270.3	16.0	0.852	0.029	254.9	15.1
5.0	0.744	0.033	288.3	23.4	0.793	0.032	284.3	23.1	0.821	0.031	275.0	22.3
5.5	0.710	0.033	290.0	31.4	0.759	0.034	295.4	32.0	0.787	0.033	292.1	31.6
6.0	0.677	0.033	289.6	40.7	0.724	0.035	303.7	42.6	0.752	0.035	306.4	43.0
6.5	0.645	0.033	287.6	51.3	0.689	0.035	309.4	55.2	0.716	0.036	317.6	56.7
7.0	0.612	0.032	284.2	63.4	0.653	0.036	312.5	69.7	0.679	0.037	325.8	72.6
7.5	0.580	0.032	279.4	76.6	0.618	0.036	313.2	85.9	0.641	0.038	331.1	90.8
8.0	0.549	0.031	273.6	91.1	0.582	0.036	311.9	103.8	0.603	0.038	333.6	111.0
8.5	0.519	0.030	266.9	106.5	0.547	0.035	308.5	123.1	0.565	0.038	333.4	133.1
9.0	0.489	0.030	259.4	122.9	0.512	0.035	303.3	143.7	0.527	0.038	330.6	156.7
9.5	0.460	0.029	251.2	140.0	0.478	0.034	296.6	165.3	0.490	0.037	325.6	181.4
10.0	0.433	0.028	242.6	157.7	0.445	0.033	288.5	187.5	0.454	0.036	318.3	206.9
10.5	0.406	0.027	233.6	175.8	0.413	0.032	279.2	210.1	0.418	0.035	309.2	232.7
11.0	0.380	0.026	224.3	194.1	0.383	0.031	268.9	232.6	0.384	0.034	298.5	258.3
11.5	0.356	0.025	214.8	212.4	0.353	0.029	257.8	254.8	0.352	0.033	286.4	283.1
12.0	0.332	0.023	205.3	230.5	0.325	0.028	246.0	276.4	0.321	0.031	273.2	306.8
12.5	0.310	0.022	195.6	248.4	0.299	0.027	233.8	296.9	0.291	0.030	259.0	328.9
13.0	0.289	0.021	186.0	265.7	0.273	0.025	221.3	316.1	0.263	0.028	244.3	348.8
13.5	0.269	0.020	176.5	282.3	0.249	0.024	208.6	333.7	0.237	0.026	229.1	366.3
14.0	0.250	0.019	167.2	298.2	0.227	0.022	195.9	349.4	0.213	0.024	213.7	381.1
14.5	0.231	0.018	158.0	313.1	0.206	0.021	183.3	363.2	0.190	0.023	198.3	392.9
15.0	0.214	0.017	149.0	326.9	0.187	0.020	170.8	374.7	0.169	0.021	183.0	401.5
15.5	0.198	0.016	140.3	339.6	0.169	0.018	158.6	384.0	0.150	0.019	168.1	406.8
16.0	0.183	0.015	131.9	351.1	0.152	0.017	146.8	390.8	0.132	0.018	153.6	408.9
16.5	0.169	0.014	123.7	361.2	0.136	0.015	135.4	395.3	0.116	0.016	139.6	407.7
17.0	0.156	0.013	115.8	370.0	0.122	0.014	124.4	397.3	0.102	0.014	126.4	403.5
17.5	0.144	0.012	108.3	377.3	0.109	0.013	114.0	397.0	0.089	0.013	113.8	396.3
18.0	0.132	0.012	101.1	383.3	0.097	0.012	104.1	394.4	0.077	0.012	102.0	386.5
18.5	0.121	0.011	94.2	387.8	0.086	0.011	94.7	389.7	0.067	0.010	90.9	374.2
19.0	0.111	0.010	87.7	391.0	0.077	0.010	85.9	383.0	0.058	0.009	80.7	359.9
19.5	0.102	0.009	81.5	392.7	0.068	0.009	77.7	374.4	0.050	0.008	71.3	343.8
20.0	0.093	0.009	75.6	393.1	0.060	0.008	70.0	364.1	0.042	0.007	62.7	326.2
20.5	0.085	0.008	70.0	392.2	0.053	0.007	62.9	352.4	0.036	0.006	54.9	307.6
21.0	0.078	0.007	64.8	390.0	0.046	0.006	56.4	339.5	0.031	0.005	47.9	288.1
21.5	0.071	0.007	59.9	386.7	0.040	0.006	50.4	325.5	0.026	0.005	41.5	268.3
22.0	0.065	0.006	55.2	382.3	0.035	0.005	44.9	310.6	0.022	0.004	35.9	248.2
22.5	0.059	0.006	50.9	376.8	0.031	0.005	39.9	295.1	0.018	0.004	30.8	228.3
23.0	0.054	0.005	46.8	370.4	0.027	0.004	35.3	279.2	0.015	0.003	26.4	208.8
23.5	0.049	0.005	43.0	363.1	0.023	0.004	31.2	263.0	0.013	0.003	22.5	189.8
24.0	0.044	0.005	39.5	355.0	0.020	0.003	27.5	246.7	0.011	0.002	19.1	171.5
24.5	0.040	0.004	36.2	346.2	0.017	0.003	24.1	230.4	0.009	0.002	16.1	154.1
25.0	0.036	0.004	33.2	336.8	0.015	0.002	21.1	214.4	0.007	0.002	13.6	137.7

Appendix I: Wind Speed Frequency Distribution Curves

Figure I1: K = 1.5

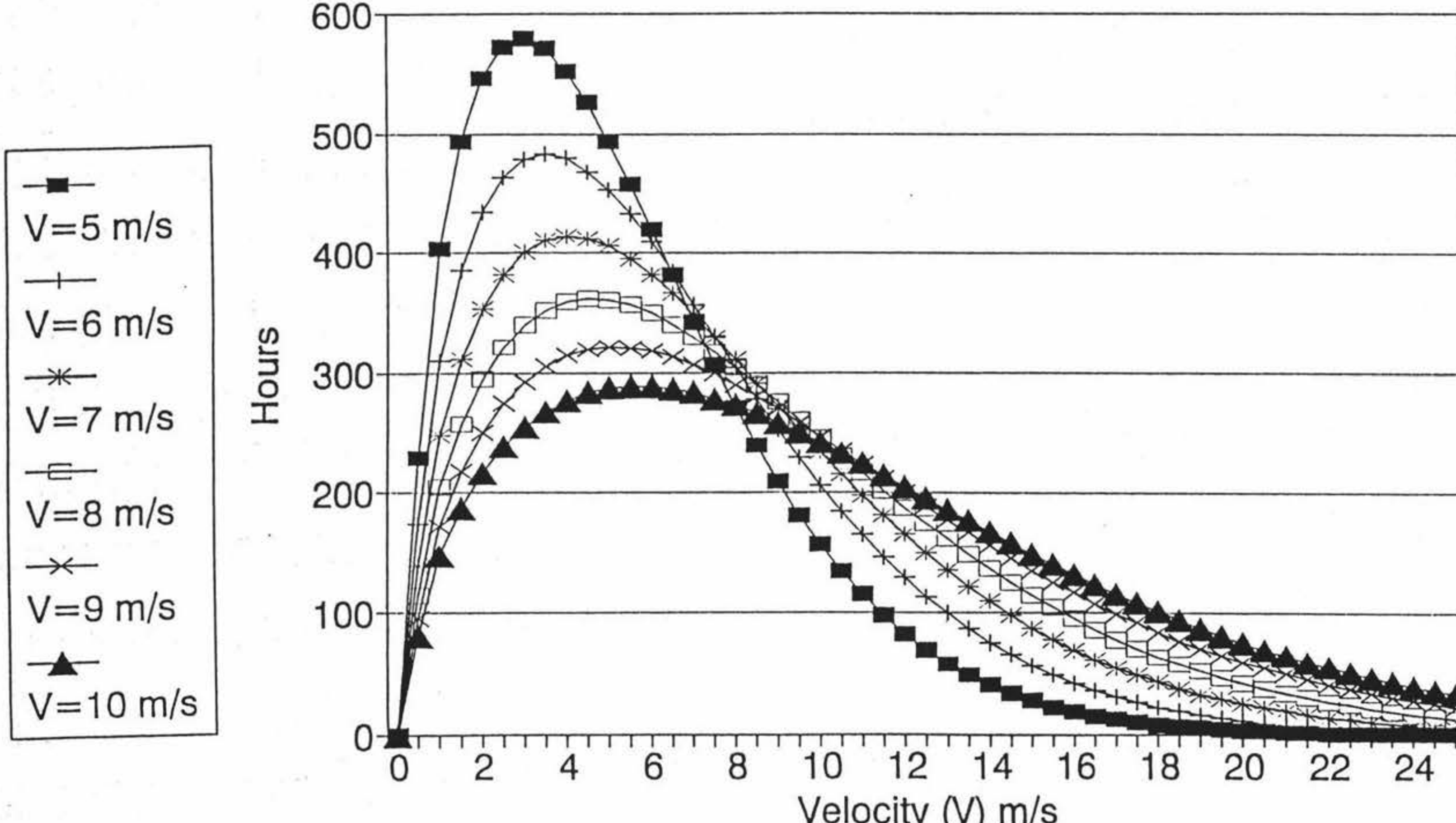


Figure I2: K = 1.8

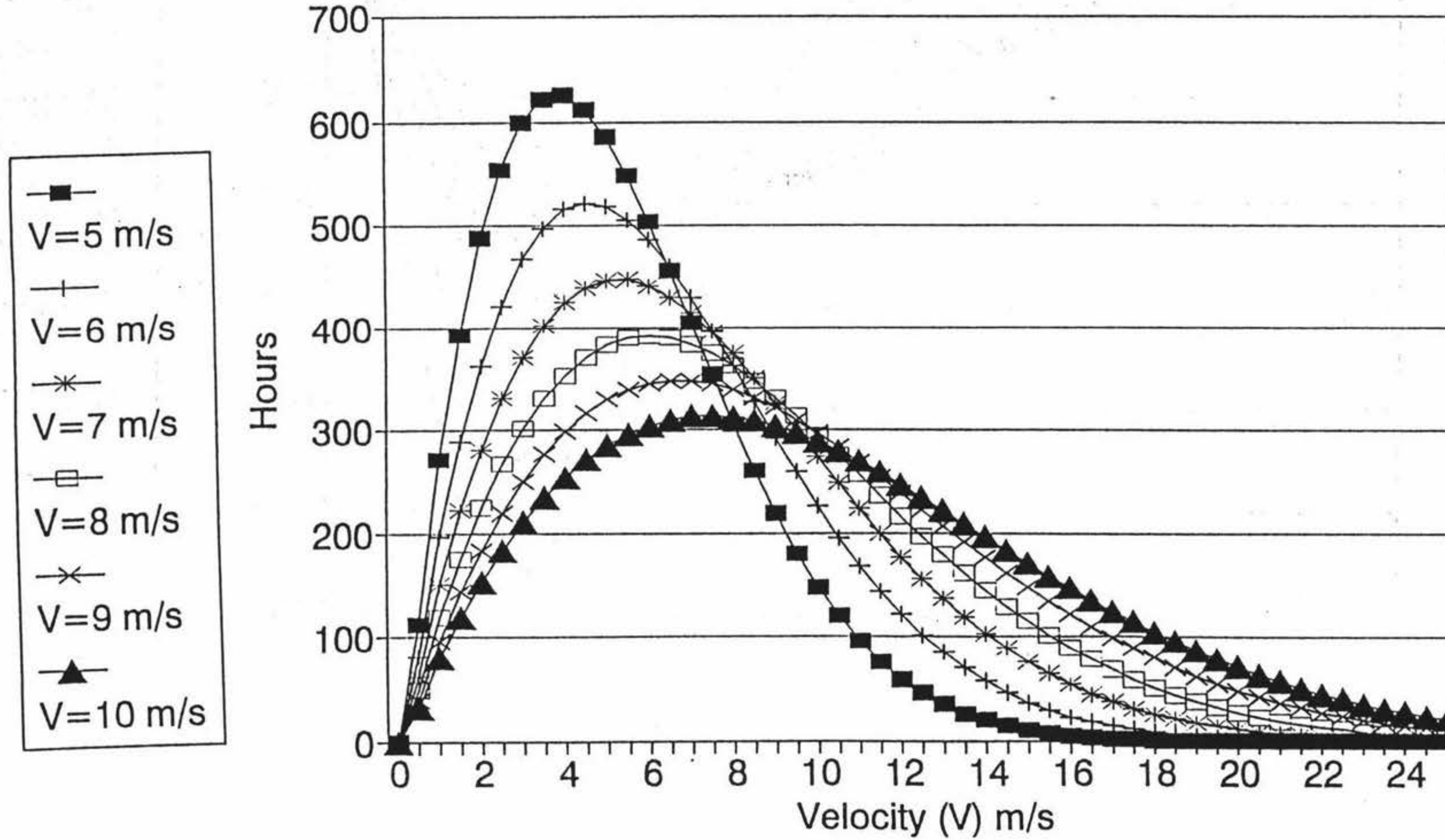
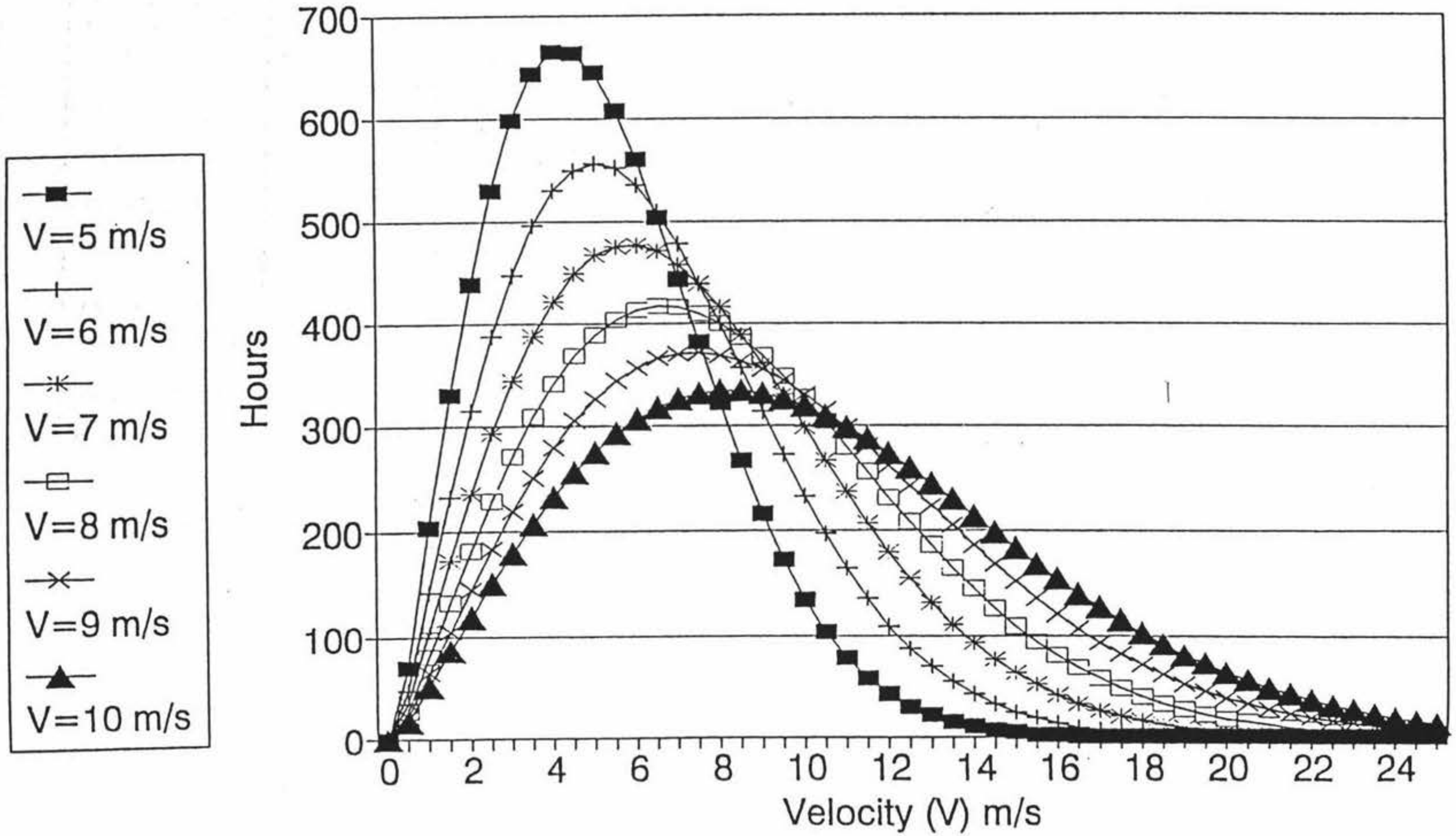


Figure I3: K = 2.0



Appendix J: Wind Power Duration Curves

Figure J1: K = 1.5

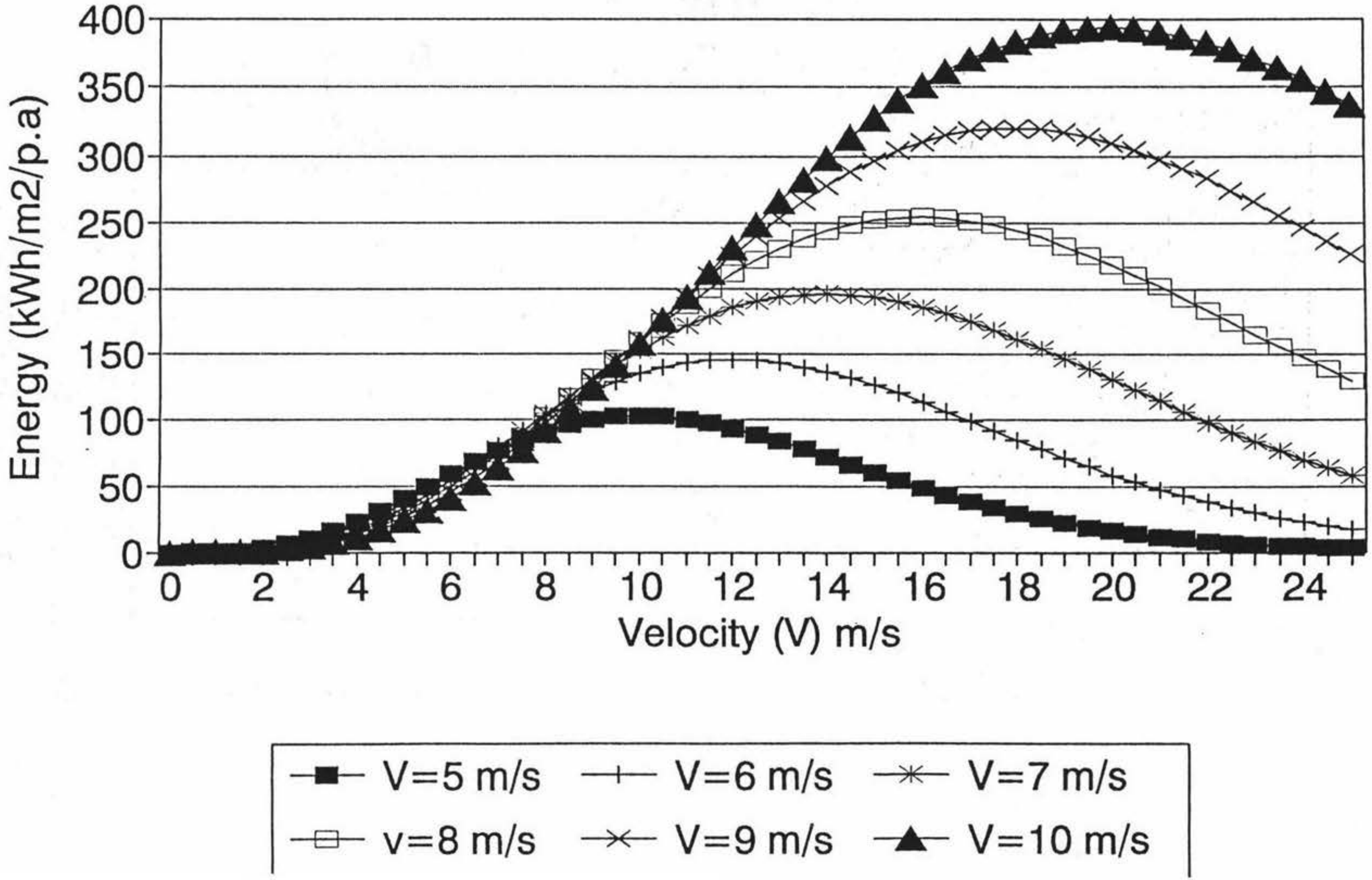


Figure J2: K = 1.8

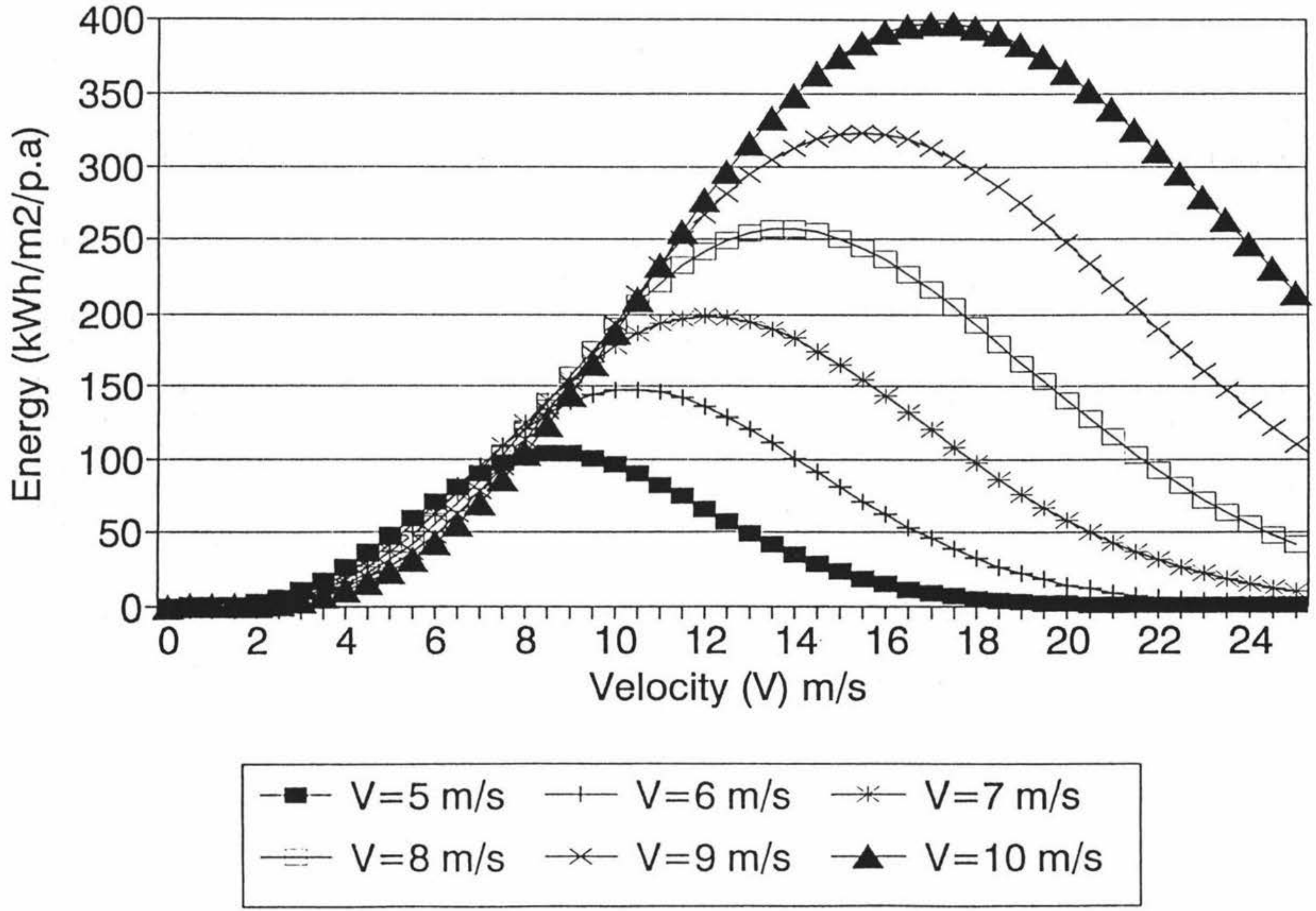
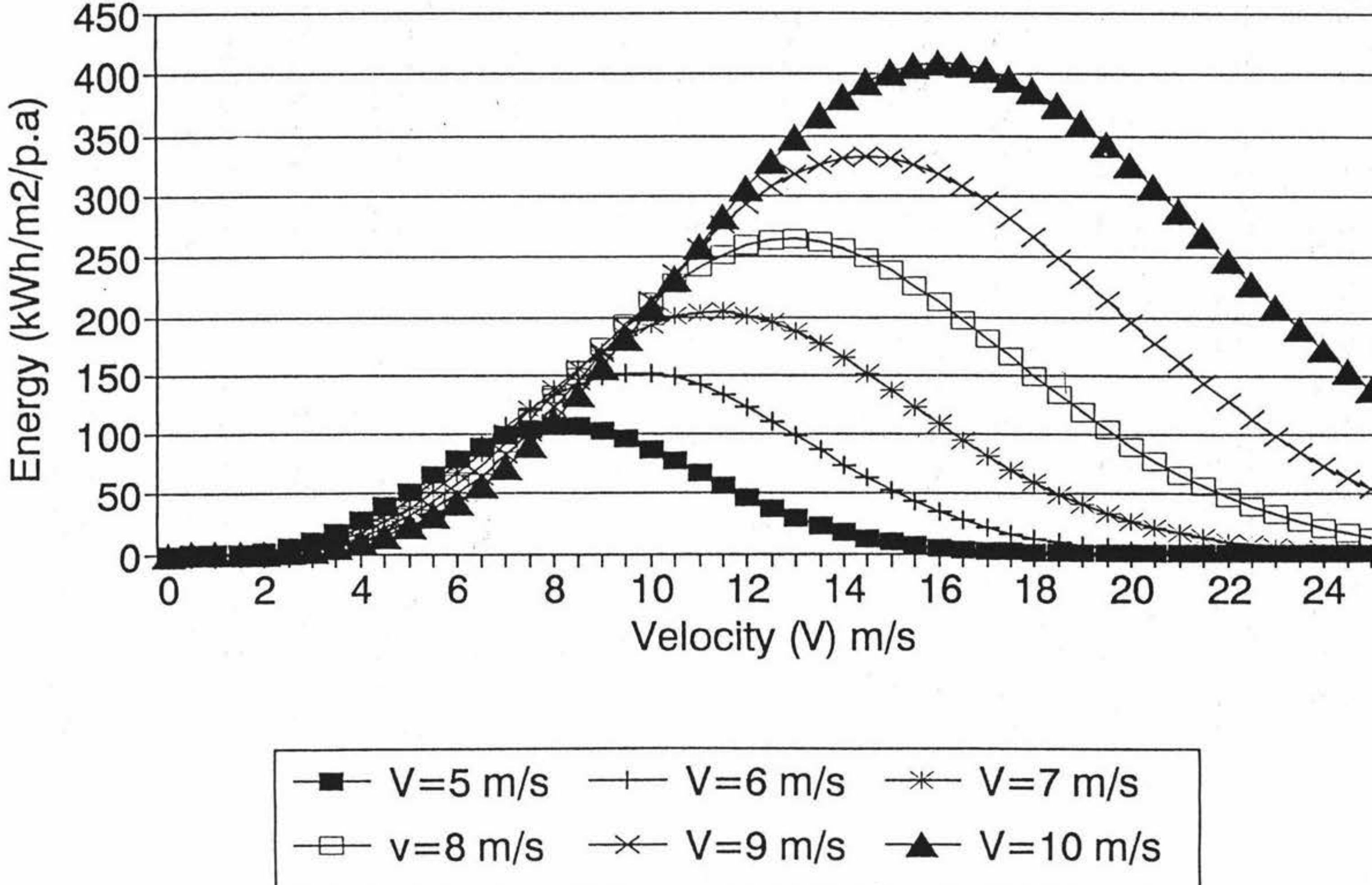


Figure J3: K = 2.0



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