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**RENEWABLE ENERGY SYSTEM DESIGN:
A GUIDE TO
THE APPLICATION OF PHOTOVOLTAIC, WIND,
AND MICRO-HYDRO POWER**

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of the requirement for the degree
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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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"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
H_c	H calculated using equations
$H_{c(\text{adj})}$	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
K_t	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
<u>or</u>	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
<u>or</u>	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
<u>or</u>	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
r_1	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