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

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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/m², 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

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

<table>
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<tr>
<td>δ</td>
<td>declination</td>
</tr>
<tr>
<td>η</td>
<td>system efficiency</td>
</tr>
<tr>
<td>η_b</td>
<td>overall battery efficiency</td>
</tr>
<tr>
<td>ρ</td>
<td>ground reflection coefficient (ground albedo)</td>
</tr>
<tr>
<td>φ</td>
<td>latitude in degrees</td>
</tr>
<tr>
<td>C</td>
<td>days of load</td>
</tr>
<tr>
<td>Symbol</td>
<td>Definition</td>
</tr>
<tr>
<td>--------</td>
<td>------------</td>
</tr>
<tr>
<td>DI</td>
<td>estimated daily demand for the month</td>
</tr>
<tr>
<td>DOD</td>
<td>maximum permissible depth of battery discharge</td>
</tr>
<tr>
<td>$G_{sc}$</td>
<td>solar constant equal to 1371 W/m²</td>
</tr>
<tr>
<td>h</td>
<td>height above sea level in km</td>
</tr>
<tr>
<td>H</td>
<td>global radiation on a horizontal surface</td>
</tr>
<tr>
<td>$H_b$</td>
<td>beam radiation on an inclined surface</td>
</tr>
<tr>
<td>Hc</td>
<td>$H$ calculated using equations</td>
</tr>
<tr>
<td>$H_{c(adj)}$</td>
<td>$H$ adjusted by the regional coefficients</td>
</tr>
<tr>
<td>$H_d$</td>
<td>diffuse radiation incident on a horizontal surface</td>
</tr>
<tr>
<td>$H_o$</td>
<td>extraterrestrial radiation on a horizontal surface</td>
</tr>
<tr>
<td>$H_r$</td>
<td>ground reflected radiation on an inclined surface</td>
</tr>
<tr>
<td>$H_s$</td>
<td>sky diffuse radiation on an inclined surface</td>
</tr>
<tr>
<td>$H_T$</td>
<td>total global amount of radiation on an inclined surface</td>
</tr>
<tr>
<td>I</td>
<td>average $H$ for the month</td>
</tr>
<tr>
<td>K</td>
<td>clearness index</td>
</tr>
<tr>
<td>$K_t$</td>
<td>monthly average clearness index</td>
</tr>
<tr>
<td>LOLP</td>
<td>loss of load probability</td>
</tr>
<tr>
<td>M</td>
<td>balancing parameter between the array and the battery</td>
</tr>
<tr>
<td>MPPE</td>
<td>mean percentage error</td>
</tr>
<tr>
<td>n</td>
<td>Julian day of the year</td>
</tr>
<tr>
<td>NSR</td>
<td>no sun ratio i.e. the ratio of the night load to the total daily load</td>
</tr>
<tr>
<td>R</td>
<td>ratio of the standard deviation in daily radiation over the average daily radiation</td>
</tr>
<tr>
<td>$R_b$</td>
<td>ratio of extraterrestrial radiation on an inclined surface to that on a horizontal surface</td>
</tr>
<tr>
<td>S</td>
<td>standard deviation of the radiation over a period of a month</td>
</tr>
<tr>
<td>$S_o$</td>
<td>monthly average daily sunshine duration</td>
</tr>
<tr>
<td>$S_{m}$</td>
<td>monthly maximum possible daily sunshine duration</td>
</tr>
<tr>
<td>W</td>
<td>watts</td>
</tr>
<tr>
<td>$W_s$</td>
<td>sunset hour angle for a horizontal plane</td>
</tr>
<tr>
<td>$W_s^1$</td>
<td>sunset hour angle for the tilted surface for the average day of the month</td>
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**WIND**

<table>
<thead>
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<tbody>
<tr>
<td>A</td>
<td>area covered by wind pump rotor</td>
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<tr>
<td>C</td>
<td>Weibull scale factor</td>
</tr>
<tr>
<td>EPF</td>
<td>energy pattern factor</td>
</tr>
<tr>
<td>f</td>
<td>frequency</td>
</tr>
<tr>
<td>F</td>
<td>factor for extrapolating wind data</td>
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</table>
H
hp
K
kWh
m
m/s
mm
n
SC
V
or
v₁
v₂
w.h
x

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
v₁: velocity at height z₁
v₂: wind velocity at height z₂
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)
Hₜ: 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
Nⱼ: number of jets
specific speed per jet
specific speed of the wheel
specific speed of the pump
power output of the turbine
flow
flow
runner radius of crossflow turbine
blade depth of crossflow turbine
blade spacing of crossflow turbine
velocity of the buckets
jet velocity in m/s
velocity of the jet
empirically derived constant to calculate required pump speed when operating as turbine

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