1. Introduction

Historically, until the initiation of central electricity supply systems, all energy systems were decentralised, i.e. power was produced at the location where and when it was required. Wind for power milling, pumping, and irrigation were commonplace. However, the availability of electricity brought about the development of grid networks with centralised generating capacity, and the demise of many decentralised power systems.

Today, we tend to forget that there are still many locations in the world which do not have electrical connection to a central utility network. Furthermore, in many places, due to remoteness and cost, it is unlikely that connection to a centralised grid will ever be established. However the need for power remains; indeed is growing as electric appliances diffuse to all parts of society. Power systems which generate and supply electricity to such remote locations are variously termed remote, decentralised, autonomous, or stand-alone.

The main aim of the model presented here is to investigate the performance of a hybrid stand-alone system for application in remote rural areas. A computer model has been developed to analyze such systems, and the required data has been obtained for a remote rural location in Bangladesh. The hybrid system considered here consists of one wind turbine, an array of PV modules and a battery bank.

2. Data requirements for the model

To undertake any modelling study, the first requirement is to collect and/or generate reasonable and appropriate input data. The input data required by this particular model are:

i) Annual hourly wind speed data, which has been generated using a software package METEONORM (version 3.0, September 1997).

ii) Annual hourly global horizontal radiation data, which has been generated using METEONORM as well.

iii) Hourly ambient air temperature, which has been generated using METEONORM as well.

iv) Wind turbine manufacturer’s data.

v) Hourly consumer load demand data collected from a rural home.

vi) PV manufacturer’s data.

vii) Battery manufacturer’s data.
3. Model description

The model consists of four sub-models: (i) wind turbine model, (ii) PV model, (iii) Storage (battery) model, and (iv) Control model. A brief description of each sub-model is given below:

3.1 Wind Turbine model

The wind turbine model is basically a look-up table where the output power of the wind turbine is determined by the wind speed (corrected to the wind turbine hub height).

Usually wind turbine power is assumed as,

\[ P(u) = f(u) \]  

where, \( P(u) \) = power of the wind turbine at wind speed \( u \), and \( f(u) \) = some suitable function of \( u \).

A typical wind turbine power curve used in this model is shown in Figure 1. The figure illustrates the relation of power output of the wind turbine used in the model with wind speed at the hub height.

![Figure 1: Typical power output of the Wind Turbine.](image)

Applying the logarithmic law for the vertical wind profile does correction of the wind speed to hub height. For simplicity, neutral stability conditions for the atmosphere are assumed and the equation used is,

\[ u(z) = u(z_{ref}) \left( \frac{\ln(z/z_0)}{\ln(z_{ref}/z_0)} \right) \]  

where, \( z \), \( z_{ref} \), \( z_0 \), \( u(z_{ref}) \), \( u(z) \) are hub height, reference height, surface roughness height, known wind speed at reference height, and wind speed at the hub height respectively.

3.2 PV model

This sub-model is developed to calculate the power output of a PV model subject to the available radiation and environmental conditions such as ambient temperature, wind speed, mounting orientation. Basically the PV model consists of the following three sub-models.

3.2.1 Thermal model

The thermal model used was originally developed by Fuentes (Fuentes, 1987) and predicts the average module temperature according to local environmental conditions. Wind speed, plane-of-array irradiation, ambient temperature and Installed Nominal Operating Cell Temperature (INOCT) are used as input parameters.

INOCT is defined as the cell temperature of an installed array at NOCT conditions (800 W/m² irradiation, 20°C ambient temperature and 1 m/s wind speed) (Gottschalg, 1999) and therefore takes into account the module mounting configuration. For example, stand-alone rack-mounted modules will clearly posses different heat flow characteristics from those designed for building integrated installations. The model initially used INOCT to establish heat gain and convective/radiative heat losses from both top and bottom module faces at NOCT conditions. These values are then modified according to the local environmental conditions. The thermal capacitance of the module is also incorporated to account for the natural temperature lag. The values used in this simulation are given in Table 1.

![Figure 2: Variation of module temperature.](image)

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>INOCT</td>
<td>40°C</td>
</tr>
<tr>
<td>Thermal Mass</td>
<td>11000 J/KgK</td>
</tr>
<tr>
<td>Emissivity</td>
<td>0.84</td>
</tr>
</tbody>
</table>

Some minor modifications have been made to the Fuentes model account for the specific geographical location. A new tilt angle has been incorporated for calculating the convective coefficient of the module top surface. The influence of this model is shown in Figure 2. The graph illustrates the relation of the ambient temperature to the module temperature for a rack-mounted system on a typical winter's day of Dhaka.

3.2.2 Cell model

Solar cells can be described in terms of parameters that are related to the physical properties of these devices. The parameters are derived from the equivalent circuit, which in
general consists of an ideal current source in parallel with two diodes and a shunt resistance. These elements are also in series with a resistance (shown in Figure 3).

The I-V characteristic of a solar cell is given implicitly by (Gottschalg, 2001),

\[ I = I_{ph} + I_{01} \left[ \exp \left( \frac{eV_i}{n_1kT} \right) - 1 \right] + I_{02} \left[ \exp \left( \frac{eV_i}{n_2kT} \right) - 1 \right] + \frac{V_i}{R_p} \] ……(3)

The voltage at the junction \( V_i \) is calculated as:

\[ V_i = V - IR_s \] ……(4)

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The remaining terms are the photo current \( I_{ph} \) in amps, the diode currents \( I_{01} \) and \( I_{02} \), the diode ideality factors \( n_1 \) and \( n_2 \), the series resistance \( R_s \) in ohms, parallel resistance \( R_p \) in ohms, model cell temperature \( T \) in K, current measured \( I \) in amps, voltage \( V \) in volts, charge of an electron \( e \), Boltzmann constant, \( k \).

Dependence of the performance on environmental conditions is not included in equation (3) since there is no crossover for an increase in temperature. This is included by modifying the photocurrent and the diode saturation currents. The photocurrent is calculated as,

\[ I_{ph} = (C_0 + C_1T)AG \] ……(5)

Here, \( C_0 \) and \( C_1 \) are two module specific constants, \( A \) is the area of the cell in \( m^2 \), and \( G \) is the irradiation in \( W/m^2 \). The variation of the diode saturation currents is linked to the band gap \( V_{gap} \) of the material, which is equivalent to 1.12 V in the case of crystalline silicon. The diode saturation currents are calculated as,

\[ I_{01} = C_0T^2 \exp \left[ \frac{V_{gap}}{kT} \right] \] ……(6)

\[ I_{02} = C_0T^{3/2} \exp \left( -\frac{V_{gap}}{2kT} \right) \] ……(7)

The equations (3-7) have been solved implicitly as described in (Press, et. al., 1992).

Maximum power point is then calculated for each curve. It is assumed for simplicity that the module operates in maximum power point (MPP).

3.3 Storage model

In principal there are many different options to store energy, but in practice the commercially available and affordable options are limited batteries. The right type of battery technology has to be selected on the basis of the application and the desired characteristics of the store. The option under consideration for medium term energy storage in conjunction with wind energy and solar energy installations for this project is the standard lead acid battery.

The battery storage may be modelled in different ways. Due to the fact that a battery is an electrochemical device with rather complex behaviour it is not easy to represent precisely. Two different types of model suited to lead acid batteries may be considered depending on the accuracy and properties which are of interest (Kacholdt, 1996 and Harman, 1997):

i) Energy transfer model,

ii) Simulation model

To avoid complexity, a straightforward energy transfer model has been used in this work. This gives the gross energy flow. It is easy to characterise from the information provided in the manufacturer’s data sheets. The disadvantage of this approach is that voltage and current cannot be calculated.

Without access to battery test facilities for characterisation purposes, the most practical approach is to develop a simple energy transfer model. The specific parameters necessary for the modelling can be obtained from the data sheet supplied with the battery under investigation. Data supplied are usually : nominal energy capacity \( (C_{nominal}) \), discharge efficiency, recommended charging rates and practices, temperature effects on the capacity of the battery, anticipated degradation of battery performance with time.

This approach is concerned primarily with the summation of energy transfer to and from the battery. The operation of the model is simple. During charging the resulting state of charge (SOC) for acceptance of an amount of energy \( E_{in} \) for a charging efficiency \( \eta_{charge} \) and nominal battery capacity \( C_{nominal} \) is,

\[ SOC = SOC + \frac{E_{in} \eta_{charge}}{C_{nominal}} \] ……(8)

When discharging an amount of energy \( E_{out} \) the resulting state of charge is given by,

\[ SOC = SOC - \frac{E_{out}}{C_{nominal} \eta_{discharge}} \] ……(9)

with \( \eta_{discharge} \) being the discharge efficiency.

The amount of energy transferred can easily be calculated using,

\[ E_{transfer} = P_{average} \cdot \Delta t \] ……(10)
where,
\[ E_{\text{transfer}} = \text{energy transfer (kWh)},\quad P_{\text{average}} = \text{average power applied during energy transfer over the time interval (kW)}, \quad \Delta t = \text{time interval (h)}, \quad \text{and} \quad E_{\text{in}} \text{ or } E_{\text{out}} \text{ may be calculated as}, \]

\[ \text{Charge or discharge loss} = F \cdot R \quad \text{……(11)} \]

where, \( I = \text{charge or discharge current in amps}, \quad R = \text{total internal resistance of the battery bank in ohms, calculated as}, \quad R = R_0 \cdot N_s/N_p \text{ with } R_0 = \text{internal resistance of a single battery cell}, \quad N_s = \text{no of cells in series}, \quad N_p = \text{no of cells in parallel}. \]

Then,
\[ \text{net } E_{\text{in}} \text{ or } E_{\text{out}} = E_{\text{transfer}} - \text{charge or discharge loss} \quad \text{……(12)} \]

The minimum SOC is usually set at least to 30% to avoid excessive damage to the batteries. A self-discharge rate (3% per month) has been considered as well.

3.4 Control model

This hybrid stand alone system is controlled in such a way that the power output from wind turbine and PV panels is used for directly meeting the consumer demand (via a suitable inverter). Excess power, if available, is stored in the battery, and energy taken from the battery is used to meet any shortfall. The control model is based solely on the state of charge (SOC) of the battery bank. A minimum SOC has been assumed in the model and at each time interval the current SOC has been calculated using equations (8) and (9). Then depending on the current SOC decision has been made whether it would charge the battery or discharge form the battery depending on the availability of power. Flowchart of the control model is shown in Figure 4.

4. Model evaluation and results

The model has been tested for a complete year of operation, for a peak load demand of 1 kW located in the rural and remote area of Dhaka, Bangladesh. The following specifications have been used in this simulation,

Wind turbine : one in number, rated output 400 W at 12 m/s, cut in speed 2.7 m/s, hub height 40 m.

PV module : twelve in number, each 75 Wp.

Battery :
- nominal voltage = 12 V
- nominal capacity = 165 Ah
- maximum discharge current = 16.5 A
- maximum charge current = 28 A
- SOC minimum = 0.3
- SOC initial = 1.0
- Self discharge = 3 % per month
- no of batteries in series = 6
- no of batteries in parallel = 2

Time step : one hour.

A typical consumer load demand curve of the area is shown in Figure 5.

Figure 5: Typical daily consumer load demand curve for a remote rural area in Dhaka.

Figure 6 shows the output of the wind turbine. The output has been calculated based on the wind speed at the 40 m hub height for the considered location. Figure 6 shows that output power from the wind turbine is generally very low. It has an annual average hourly output of 29.5 W and daily average output of 708 Wh.
Power output of the twelve PV panels is shown in Figure 7. All the panels were mounted at an elevation of 23.28° (the latitude angle of Dhaka), facing due South. The calculated annual average hourly output of the PV modules is 107.85 W and the daily average is 2588 Wh.

![Figure 7: Total output power from the PV panels.](image)

Energy available for charging the batteries, and also needed to cover any deficit (i.e. to be discharged from the battery) are shown in Figure 8 (only a typical portion of the year is shown in the figure for clarity). The annual average energy available for charging is 941.24 kWh, whereas total shortfall is 975.87 kWh. This indicates an overall deficit in the energy supplied from the battery bank, as shown in Figure 9. The system has a capability to meet the load demands of consumers for only 6153 hours in a year (70%), and during the rest of the time load shedding is required.

![Figure 8: Power available for storage (charge) and shortage (discharge).](image)

![Figure 9: Dump and Deficit power of the Battery bank.](image)

The power losses incurred due to charging and discharging are shown in Figure 10. The annual average hourly discharge loss is 2.66 W, and charging loss, 1.56 W.

![Figure 10: Charge and Discharge losses of the Battery bank.](image)

The state of the charge of the battery bank is shown in Figure 11. With a minimum SOC of 0.3 specified for the controller, it is clear that this lower bound is always exceeded.

![Figure 11: State of Charge (SOC) of the Battery Bank.](image)

5. Economic analysis

As the elements of a hybrid stand alone system is relatively costly, an economic analysis has been done for the feasibility study of the project. In the economic assessment (Table 2) the costs of the individual items have been considered as per present local market prices and the indicators have been calculated for an annual discount rate of 10% using the methods described in (Hunter and Elliot, 1994).

<table>
<thead>
<tr>
<th>Cost elements</th>
<th>Tk.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Twelve PV modules @ Tk. 20,000.00</td>
<td>240,000.00</td>
</tr>
<tr>
<td>One wind turbine</td>
<td>100,000.00</td>
</tr>
<tr>
<td>Twelve batteries (each 7 years life) @ Tk. 6,000.00</td>
<td>144,000.00</td>
</tr>
<tr>
<td>Others</td>
<td>20,000.00</td>
</tr>
<tr>
<td><strong>Total investment cost</strong></td>
<td><strong>504,000.00</strong></td>
</tr>
<tr>
<td>Revenue income per year*</td>
<td>207,000.00</td>
</tr>
<tr>
<td>O &amp; M cost per year</td>
<td>40,000.00</td>
</tr>
<tr>
<td>Net revenue income per year</td>
<td>167,000.00</td>
</tr>
</tbody>
</table>

* @ Tk. 150.00 per lamp per month, about 115 lamps to be connected, each 6 W for 4 hours operation per day.

Note: US$1.00 = Tk. 70.00 (Tk. stands for Bangladeshi currency).
5. Conclusions

A hybrid stand-alone system has been modelled for a remote rural area of Bangladesh where the peak consumer load demand is around 1 kW. The system consists of a 400 W wind turbine, twelve 75 Wp PV modules and one battery bank comprising of 12 V lead acid batteries, giving a total capacity of 1980 AmpHours or 23.76 kWh. The results reveal that the system is capable of meeting the full consumer load demand for 70% time of the year, and for the rest of the time a degree of load shedding is required. This is mainly because of low wind speed available at the site considered which makes it difficult to justify a larger wind turbine. The estimated cost of electricity per kWh is Tk. 47.00, and the simple pay back period is 3 years with an IRR of 30.89%.

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References


