ANALYSIS OF RENEWABLE ENERGY SOURCES IN RAJASTHAN, INDIA WITH EMPHASIS ON SIZING AND COST OPTIMIZATION

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A Project

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Suresh K Vadhva, Ph.D                                                                   Date

Department of Electrical and Electronic Engineering
Abstract

of

ANALYSIS OF RENEWABLE ENERGY SOURCES IN RAJASTHAN, INDIA WITH EMPHASIS ON SIZING AND COST OPTIMIZATION

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In today’s world, due to the growing demands of technology and rise in population, there has been a tremendous pressure on the electricity demands. So far fossil fuels have been used to meet the demands, but since fossil fuels are finite and are getting depleted, the world needs to find alternative sources of energy. Also the use of fossil fuels like natural gas and oil has a hazardous effect on the environment because of the chemicals which pollute the air. Hence renewable sources such as solar energy, wind energy, biomass, etc. are being considered to meet the growing demands of energy.

The ultimate goal of the project is find the best design in terms of cost for installing a power plant at any location considering the average hourly load profile of that location. Stand alone power systems are mainly benefited by small far away villages where it is difficult to supply power through the grid. This report aims at analyzing the renewable energy sources available in Rajasthan, India to help the small villages avail electricity. Sizing of the solar panels and wind turbines is of utmost importance. The report designs an algorithm which aims at calculating the size of solar alone, wind alone and solar-wind
hybrid systems. This algorithm takes into consideration the average hourly profile of a small village in Rajasthan along with the average hourly insolation and wind profile of the same. This algorithm helps decide the minimum number of PV panels required for a solar alone design and number of wind turbines required for a wind alone design. The code also helps to decide how many PV panels and wind turbines are required for a hybrid design.

Cost optimization plays a major role in designing a standalone power plant. The cost optimization with the help of sizing is a deciding factor of which design (solar alone, wind alone or hybrid) is suitable for a particular location. After calculating the size, cost optimization decides, which design will be the most optimum one to install. In this project it helps decide a standalone plant for small villages in Jaisalmer. By using our analysis, one can decide the best design in terms of size and cost to install stand alone power plants.

------------------------------------------, Committee Chair
John C. Balachandra, Ph.D

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Date
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Chapter 1

INTRODUCTION

1.1 Why renewable energy sources?

There has been a tremendous growth in technology and population of the world. Energy and development are closely intertwined, resulting in increased use of fossil fuels, such as gas, petrol and coal which cannot be replenished or renewed.

This ultimately leads to an increase in the usage of electricity. Electricity is mainly generated from non-renewable energy sources like crude oil, natural gas, coal etc. These are termed as non-renewable since they are finite and cannot match up to the needs of the world. The oil reserves of the world will not sustain in the time to come. Currently these sources are there in abundance, but will diminish in the near future because of the increasing demand of electricity.

Even if these sources are available in quantity, the non renewable energy sources have a big negative impact on the environment. They produce immense toxic waste and pollute the environment to a great extent. It is detrimental to plant and animal life. The usage of fossil fuels is one of the reasons for global warming. Electricity generated from fossil fuels and coals result in harmful emissions of nitrogen oxides and sulphur dioxides. These chemicals lead to acidic rivers and are lethal to mankind [1].
All the above indicates us to discover alternate sources of energy. These alternate sources of energy are the renewable energy sources which are available in ample quantity. Renewable sources of energy mainly consist of solar energy, wind energy, biomass, geothermal and hydropower [2]. As technology progresses, there have been efficient means to abstract electricity from the above mentioned renewable sources.
1.2 Advantages of Renewable Energy Sources

- Renewable Energy Sources such as solar energy, wind energy, geothermal energy and biomass are replenished constantly. That is they are not exhaustible and available in abundance.
- They do not support global warming.
- These energy sources are available for free.
- These sources produce minimal toxic waste and hence do not pollute the environment in a negative way. They are a clean source of energy since they do not contribute to air pollution [3].
- Renewable power plants are located far away from the suburbs in cities which brings economic benefits in many regional places [4].
- Operational cost of the power plants are less since the source of energy is acquired in a natural way. Because of which the maintenance cost is also reduced [3].
1.3 Disadvantages of Renewable Energy Sources

Renewable energy sources are definitely more beneficial than the non-renewable energy sources. But, renewable sources have their own shortcomings because of which they aren’t used as widely as fossil fuels. The following are the reasons which have hindered their use on a wide scope.

- Solar energy is the optimum source of energy to produce electricity but the initial cost of manufacturing photovoltaic panels is very high.
- Solar panels need to be installed in a large and open area and is optimum only for locations receiving a plethora of sunlight.
- Solar energy production is not possible as night. Hence requires the use of batteries or hydrogen fuel cell to store electricity.
- Wind turbines are generally noisy in operation. Hence it contributes to noise pollution.
- Wind turbines could be dangerous for birds. [1]
1.4 Renewable Energy Status in India

India has ample resources of renewable energy. “It is the only country in the world to have an exclusive ministry for renewable energy development, the Ministry of Non-Conventional Energy Sources (MNES).” [5].

![India’s Oil Production and Consumption 1990-2009*](image)

Source: U.S. Energy Information Administration *2008-09 is forecast

Figure 1.1 India’s Oil Production and Consumption

India stands at the 4th position in the world in terms of purchasing power from other countries. This is mainly due to the overgrowing population of the country. Figure above indicates that India’s oil consumptions are more than the oil the country is able to produce [6]. Hence it has to depend on its imports for its petroleum demands. This
shows that India has had a negative balance for years. This is mainly due to India’s overgrowing population.

Figure 1.2 Total Energy Consumption in India

Figure above shows the breakdown of the resources for producing electricity in India [6]. The figure indicates that India highly depends on coal for its electricity production followed by oil which accounts for 31% of the total energy consumption. Apart from hydroelectric power, other renewable sources account for only 1% of the total consumption. This number can be increased tremendously since India is one of the countries which have low cost of manpower with skilled labor. Hence it is one of the
locations which are most suitable to utilize the abundance of renewable energy sources available in the country.

India is a land of villages. Developing stand alone renewable systems to these villages will surely benefit the country since till date many of these villages do not receive sufficient electricity for their daily needs.
Chapter 2

THEORY AND APPLICATION

2.1 Solar Energy

The scarcity of electricity in rural areas and the need for low cost power is driving the world towards the photovoltaic industry. Solar energy is one of the most prominent renewable sources of power generation in the world. It can be utilized in various methods and for different applications. In today’s world PV can be used for a wide number of applications such as supplying electricity in remote villages, water pumping and navigation purposes for the coast guard [7]. Figure below shows a typical solar panel installed on a house which is remotely located [8].

Figure 2.1 Installed Solar Panels
Description of Photovoltaic Systems:

Photovoltaic systems consist of photovoltaic cells, which are devices that convert light energy directly into electricity. As they use sunlight as a source of energy they are known as solar cells. Photovoltaic Cells (PV) are made of at least two layers of semiconductor material mostly amorphous silicon, positive and negative. When sunlight falls on the semiconductor cells they generate electricity. Photons are produced by the sunlight. “The photons hit the cell and produce free electrons that move through the wires and cause an electric current” [9]. Figure below shows how a solar panel produces electricity [9].

Figure 2.2 Solar Panel Circuits
2.2 Wind Energy

**Wind Energy Background:**

Wind is the most prominent renewable source of energy, as it can produce electricity with natural wind, rather using non renewable sources of energy such as fossil fuels. It is also clean form of energy production, which does not emit pollution, thereby not destroying nature. Wind turbines produce significant amount of energy using only the wind. In near future, wind energy will be one of the most important sources of energy for faster development. The energy production with the wind turbines depends on the average speed of the wind in a specific area. Areas near the coast and open terrain have more flow of wind. The usage of wind turbines for energy generation is increasing day by day with a rapid growth in the past 25 years. About 25,000 MW is estimated to be in use around the world.

**Description of Wind Turbines:**

A modern wind turbine works on the same conventional principle as windmills work, using the natural wind to turn the blades for the production of electricity. A typical wind turbine is made up of four components, a rotor and two or three propellers, covered housing for engine, connecting cables and electric monitoring equipments. The rotor, blades and the nacelle are mounted on top of the tower and the monitoring equipments are throughout the system [14].
A rotor is pivoted with three propellers or blades known as airfoils. The wind moves the blades eventually spinning the rotor. The faster the wind blows, the better the spinning of the rotor. Electricity is produced when the rotor spins in the housing and the rotor is connected to a gearbox with low speed axle, increasing the speed of rotation. The gearbox on the other side is connected with high speed axle spinning the generator to produce electricity. An electromagnet attached to the axle rotates within a wired mesh, creating magnetic field which produce strong electric current [14].

Cables carry the electric current to the base of the tower and the transformer steps up-down the voltage according to the usage on site. Control systems and other electronics monitor, manage, and optimize turbine operations. They also optimize the energy production according to the wind conditions [14].

Figure below shows the basic construction of a wind turbine [14].
Figure 2.3 Construction of Wind Turbine
2.3 Stand Alone Hybrid Systems

Stand alone hybrid systems consist of electricity produced by solar and wind energy. Since wind and solar insolation occur naturally, they cannot be totally replaced by fossil fuels altogether. There are many locations where there is more wind and less sunshine in the winter season and locations where there is plenty of sunshine in the summer but rarely any wind. So there needs to be a provision during worst case situations as explained. Having a wind turbine and solar panels produce electricity together eliminates the drawbacks of a standalone solar/wind system. This ensures load is met. When the electricity supply demands are not met, a backup diesel generator is also used to meet the demands [11].

Figure 2.4 Hybrid Power System
Figure above shows a hybrid power system [10]. The system consists of solar panels, wind turbines, battery bank and a generator. The battery bank is used to store any excess electricity generated which can be used at low periods. And the backup generator starts working when there is no charge left in the battery.
Chapter 3

METHODOLOGY

3.1 Flowchart

Figure 3.1 Flowchart
3.2 Algorithm

The steps involved for choosing the number of wind turbines and solar panels are as follows:

- Find the average power demand of the location.
- Find the average hourly wind, solar insolation of location under study. Depending upon the available data, the number of wind and solar turbines should be selected such that the power generated by these devices should match the actual power demand of that area.
- The number of wind turbines should be kept as minimum as possible because the ratings of the wind turbines are much greater than that of solar panels.
- Select the appropriate combination of wind turbines and solar panels by selecting ‘n’ number of wind turbines and increasing the number of solar panels such that over a given period of time, the power deficit/surplus (the average hourly mean value of the difference between the power generated and power demand) for wind turbines or solar panels or combination of both should be zero.
- For selecting various combination of devices, following three cases are consider:
Case I: Wind Alone power generating system (zero solar panels):
Select ‘n’ number of wind turbines such that the graph of power deficit (wind turbines) for ‘n’ number of wind turbines should be equal to or greater than zero.

Case II: Solar Alone power generating system (zero wind turbines):
Select a number of solar panels such that the graph of power deficit (solar panels) for solar panels should be equal to or greater than zero.

Case III: Hybrid (wind and solar) power generating system:
Here, ‘n-1’ wind turbines are selected because the power deficit of ‘n’ wind turbines will be positive indicating that any combination of ‘n’ wind turbines and 1 or more solar panels will always be positive. So, select combination of ‘n-1’ wind turbines and particular number of solar panels for power deficit/surplus to be equal to or greater than zero.

1. Select a single wind turbine and increase the number of solar panels such that the graph of power deficit (solar panels and wind turbines) for single wind turbine and solar panels should be equal to or greater than zero.
2. Now, select two wind turbines and increase the number of solar panels such that the graph of power deficit/surplus (solar panels and wind turbines) for two wind turbines and solar panels should be equal to or greater than zero.

3. Repeat the above step till ‘n-1’ number of wind turbines.

- Calculate the average power deficit/surplus for each hour of the day.
- Calculate the average daily energy for each combination from the power deficit/surplus data obtained in each case above.
- Calculate the annual cost of every combination above and select the combination which has the lowest price.
Chapter 4
CALCULATIONS AND SIMULATIONS

4.1 Load Demand

Load energy profile is daily recorded for a period of 1 month and then the average hourly load profile is calculated. Figure below shows the typical average load demand of a small village on hourly basis.

Figure 4.1 Average Hourly Load Demand
4.2 Formulas and Specifications

1. General formula and specifications for output power generated by a single PV Panel are as follows:

<table>
<thead>
<tr>
<th>Maximum Power</th>
<th>120 W</th>
</tr>
</thead>
<tbody>
<tr>
<td>Efficiency</td>
<td>12 %</td>
</tr>
<tr>
<td>Area</td>
<td>1.07 m²</td>
</tr>
<tr>
<td>Total Capital Cost</td>
<td>$614</td>
</tr>
</tbody>
</table>

Table 4.1 PV Panel Parameters

Output power generated by a single PV panel is calculated using the following equation. The equation below ignores the temperature effect on PV cells [12].

\[ P_{pv}(t) = I_{s}(t) * A * \text{Eff}_{pv} \]

Where,

\[ I_{s}(t) = \text{Insolation data at time } t \text{ in } \text{KW/m}^2 \]

\[ A = \text{Area of a single panel in } \text{m}^2 \]

\[ \text{Eff}_{pv} = \text{Efficiency of the PV panels.} \]
The graph below shows the average hourly solar insolation data for a day in the month of March at Jaisalmer, Rajasthan [17].

Substituting the insolation values from the above figure and the PV panel parameters in the above equation we can plot the output power generated by a single PV panel at each hour. These values have been generated from the code given in topic 4.5.
2. General formula and specifications for output power generated by a single wind turbine are as follows:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated Power</td>
<td>10 KW</td>
</tr>
<tr>
<td>Rotor Diameter</td>
<td>7 m</td>
</tr>
<tr>
<td>Wind Turbine Efficiency (Cp)</td>
<td>30% Assumed</td>
</tr>
<tr>
<td>Air density</td>
<td>1.225 kg/m3</td>
</tr>
<tr>
<td>Effad</td>
<td>95% Assumed</td>
</tr>
<tr>
<td>Total Capital Cost</td>
<td>$20000</td>
</tr>
</tbody>
</table>

Table 4.2 Wind Turbine Parameters
Output power generated by a single wind turbine is calculated using the following equation [12].

\[ P_{\text{Wind}}(t) = \frac{1}{2} \rho A v(t)^3 C_p \text{Eff}_{\text{ad}}, \]

Where,

\( \rho = \) air density in kg/m³
\( A = \) swept area of the motor in m²
\( v = \) wind speed in m/s
\( C_p = \) efficiency of the wind turbine
\( \text{Eff}_{\text{ad}} = \) efficiency of the converter

The graph below shows the average hourly wind data measured at the given site which in this case is Jaisalmer, Rajasthan [18].
Substituting the hourly average wind speed from above figure and the wind turbine parameters in the wind equation we can plot the power output generated at each hour by a single wind turbine. These values have been generated from the code given in topic 4.5.

Figure 4.4 Average Hourly Wind Profile
3. General formula for Power deficit/surplus is as follows:

Power deficit/surplus is obtained by taking difference between power generated and power demand which is given as follows:

\[
\text{Power deficit/surplus} = \text{Power Generated} - \text{Power Demand}
\]

4. Battery Specifications

<table>
<thead>
<tr>
<th>Type</th>
<th>Deep Cycle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage</td>
<td>12 V</td>
</tr>
<tr>
<td>Capacity</td>
<td>100 Ah</td>
</tr>
<tr>
<td>Rating</td>
<td>1200 W = 1.2KW</td>
</tr>
<tr>
<td>Price</td>
<td>$225</td>
</tr>
</tbody>
</table>

Table 4.3 Battery Specifications
5. General formula for calculating number of batteries is as follows:

\[
\text{Number of batteries} \geq \frac{\text{Required Storage Capacity}}{(0.8) \text{ (rated capacity of each battery)}}
\]

where, 0.8 means batteries should not be cycled more than 80% of their rated capacity.

4.2 Simulations
The codes used for simulation and to obtain the following graphs are given in topic 4.5.
The three cases for different combination of wind turbines and PV panels are as follows:

**Case I**: Wind Alone power generating system (zero solar panels):
The number of wind turbines required for the balanced system (power deficit/surplus = 0) can be obtained from the following graph:

![Figure 4.6 Graph of Deficit/Surplus Power produced by ‘n’ no. of wind turbines](image)

Figure 4.6 Graph of Deficit/Surplus Power produced by ‘n’ no. of wind turbines
From the graph, it is clear that 3 wind turbines are required for the system to meet the load i.e. power deficit/surplus to be equal to or greater than zero. So, the value of ‘n’ for wind turbines is 3 i.e. ‘n’ = 3.

Also, the graph of average daily power deficit/surplus obtained by using the power deficit/surplus equation is as follows:

![Graph of average Deficit/Surplus Power at each hour of the day](image)

Figure 4.7 Graph of average Deficit/Surplus Power at each hour of the day

The above graph of average daily power deficit/surplus can be used to obtain average daily energy curve by taking hourly summation of power deficit/surplus for the entire day.
Figure 4.8 Average Daily Energy Curve for Wind Alone Design

From the above graph, it is clear that the difference in the peak to peak values of energy curve is 14.39KWh.

So, the number of batteries can be calculated from the batteries equation as

Number of batteries $\geq$ Required Storage Capacity

$(0.8)$ (rated capacity of each battery)
\[ \frac{14.39}{0.8 \times 1.2} = 14.98 \]

\[ = 15 \]

**Case II:** Solar Alone power generating system (zero wind turbines):

The number of solar panels required for the balanced system (power deficit/surplus = 0) can be obtained from the following graph:

Figure 4.9 Graph of Deficit/Surplus Power produced by ‘n’ no. of PV Panels
From the graph, it is clear that 64 solar panels are required for the system to meet the load i.e. power deficit/surplus to be equal to or greater than zero.

Also, the graph of average daily power deficit/surplus obtained by using the power deficit/surplus equation is as follows:

Figure 4.10 Graph of Average Deficit/Surplus Power at each hour of the day

The above graph of average daily power deficit/surplus can be used to obtain average daily energy curve by taking hourly summation of power deficit/surplus for the entire day.
Figure 4.11 Average Daily Energy Curve for Solar Alone Design

From the above graph, it is clear that the difference in the peak to peak values of energy curve is 22.34KWh.

So, the number of batteries can be calculated from the batteries equation as

$$\text{Number of batteries} \geq \frac{\text{Required Storage Capacity}}{0.8 \times \text{Rated capacity of each battery}}$$

$$= \frac{22.34}{0.8 \times 1.2}$$

$$= 23.27$$

$$= 24$$
Case III: Hybrid (wind and solar) power generating system:

In Hybrid power generating system, the number of solar panels is determined by increasing wind turbines in each step until ‘n-1’ and using the power deficit/surplus formula. From Case I, the value of n was obtained as 3. So, the number of solar panels must be calculated for 2 cases:

- Number of solar panels with 1 wind turbine.
- Number of solar panels with 2 wind turbines.

I. Number of solar panels with 1 wind turbine:

The number of wind turbines and solar panels required for the balanced system (power deficit/surplus = 0) can be obtained from the following graph:
Figure 4.12 Graph of no. of PV Panels required in Hybrid Design I

From the graph, it is cleared that 47 solar panels are required for the system to be stable i.e. power deficit/surplus to be equal to or greater than zero.

Also, the graph of average daily power deficit/surplus obtained by using the power deficit/surplus equation is as follows:
Figure 4.13 Graph of Average Deficit/Surplus Power at each hour of the day

The above graph of average daily power deficit/surplus can be used to obtain average daily energy curve by taking hourly summation of power deficit/surplus for the entire day.
Figure 4.14 Average Daily Energy Curve for Hybrid Design I

From the above graph, it is clear that the difference in the peak to peak values of energy curve is 19.33KWh.

So, the number of batteries can be calculated from the batteries equations as

\[
\text{Number of batteries} = \frac{19.33}{0.8 \times 1.2} \approx 20.13
\]

\[
= 21
\]
II. Number of solar panels with 2 wind turbine:

The number of solar panels required for the balanced system (power deficit/surplus = 0) can be obtained from the following graph:

![Graph of No of PV Panels required in Hybrid Design II](image)

Figure 4.15 Graph of No of PV Panels required in Hybrid Design II

From the graph, it is clear that 31 solar panels are required for the system to meet the load i.e. power deficit/surplus to be equal to or greater than zero.

Also, the graph of average daily power deficit/surplus obtained by using the power deficit/surplus equation is as follows:
Figure 4.16 Graph of Average Deficit/Surplus Power at each hour of the day

The above graph of average daily power deficit/surplus can be used to obtain average daily energy curve as follows:
From the above graph, it is clear that the difference in the peak to peak values of energy curve is 17.08KWh.

So, the number of batteries can be calculated from the batteries equation as

Number of batteries = 18/(0.8*1.2)

= 17.79

= 18
4.4 Results

The following are the sizing requirements for various designs in order to meet the load.

<table>
<thead>
<tr>
<th>Design Type</th>
<th>No of Wind Turbines</th>
<th>No of PV Panels</th>
<th>No of Batteries</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wind Alone</td>
<td>3</td>
<td>0</td>
<td>15</td>
</tr>
<tr>
<td>Solar Alone</td>
<td>0</td>
<td>64</td>
<td>24</td>
</tr>
<tr>
<td>Hybrid I</td>
<td>1</td>
<td>47</td>
<td>21</td>
</tr>
<tr>
<td>Hybrid II</td>
<td>2</td>
<td>31</td>
<td>18</td>
</tr>
</tbody>
</table>

Table 4.4 Result of Sizing Algorithm

4.5 Codes:

The programming and simulation of the above formulas is done in Matlab. The various codes used to generate the graphs in topic 4.2 and topics 4.3 are as follows:

**Case I:** Wind Alone power generating system (zero solar panels):

The code for wind alone configuration is used to generate the following graphs:

- Figure 4.5 Graph of output of a single wind turbine at each hour of the day
- Figure 4.6 Graph of Deficit/Surplus Power produced by ‘n’ no. of wind turbines
- Figure 4.7 Graph of Average Deficit/Surplus Power at each hour of the day
- Figure 4.8 Average Daily Energy Curve for Wind Alone Design
**Code:** The code for wind alone power generating system is as follows:

```matlab
% Input wind data
wind=[3.4 3.3 3.2 3.4 3.2 3.5 3.2 3.3 3.6 3.4 3.8 4.77 5 5.2 5.7 5.75 5.5 4.5 4.1 4.2 3.9 3.8 3.7 3.6];

% Power demand
Power_demand=[1.4 1.2 1.2 1.25 1.3 1.6 2 2.8 2.5 2.2 2 1.8 1.75 1.7 1.6 1.6 1.8 2.4 2.6 2.65 2.5 2.45 2.25 1.7];

% Calculation parameters
p=.5*1.225*.95*.4*38.48;

for in=1:24
    Power(in)=p*wind(in)*wind(in)*wind(in); %Power generated by wind turbine
end

% Plotting
subplot(1,4,1)
plot(time,Power)
plot(time,wind)

for i=1:3
    Power_generated=(Power * i)/1000;
    Deficit(i)=mean(Power_generated-Power_demand); % power surplus/deficit
end

temp=find(Deficit>0 )

% temp_defecit=((Power*2)/1000-Power_demand)
% i=[1 2]
```
Deficit(1)

Deficit(2)

Deficit(3)

i=[1 2 3]

subplot(1,4,2);

plot(i(1),Deficit(1),'r+',i(2),Deficit(2),'r+',i(3),Deficit(3),'r+')

a=temp(1);

temp_defecit=((Power*a)/1000-Power_demand);

temp=0;

temp(1)=temp_defecit(1);
temp(2)=temp_defecit(2)+temp_defecit(1);

% temp(2)=defecit(2)+ temp(1)

for in=3:24

    temp(in)=temp(in-1)+ temp_defecit(in);

end

integrate_defecit=temp;

subplot(1,4,3)

plot(temp_defecit)
Case II: Solar Alone power generating system (zero wind turbines):

The code for solar alone configuration is used to generate the following graphs:

Figure 4.3 Graph of output of a single PV panel at each hour of the day
Figure 4.9 Graph of Deficit/Surplus Power produced by ‘n’ no. of PV Panels
Figure 4.10 Graph of Average Deficit/Surplus Power at each hour of the day
Figure 4.11 Average Daily Energy Curve for Solar Alone Design

**Code:** The code for solar alone power generating system is as follows:

```matlab
time = [1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24];
solar = [0 0 0 0 0 .08 .15 .38 .53 .67 .75 .59 .41 .34 .21 .09 0 0 0];
Power_demand = [1.4 1.2 1.25 1.3 1.6 2 2.5 2 1.8 1.75 1.7 1.6 1.8 2.4 2.6 2.65 2.5 2.45 2.25 1.7];

Power = .12*1.07*solar
```

```matlab
subplot(1,4,1)
plot(time,Power)
plot(time,solar)
```
```
solar_deficit = Power - Power_demand

for i = 1:150
    Power_generated = (Power * i);
    Deficit(i) = mean(Power_generated - Power_demand);
end

a = find(Deficit > 0);
temp = a(1);
Deficit_power = (Power * temp - Power_demand)
    subplot(1,4,2)
    plot(Deficit)
    subplot(1,4,3)
    plot(Deficit_power)

    temp = 0;
    temp(1) = Deficit_power(1);
    temp(2) = Deficit_power(2) + Deficit_power(1);
    for in = 3:24
        temp(in) = temp(in-1) + Deficit_power(in)
```
end

integrate_solar=temp;

subplot(1,4,4)
plot(integrate_solar)

**Case III:** Hybrid (wind and solar) power generating system:

The code for Hybrid (wind and solar) configuration is used to generate the following graphs:

- Figure 4.12 Graph of no. of PV Panels required in Hybrid Design I
- Figure 4.13 Graph of Average Deficit/Surplus Power at each hour of the day
- Figure 4.14 Average Daily Energy Curve for Hybrid Design I
- Figure 4.15 Graph of No of PV Panels required in Hybrid Design II
- Figure 4.16 Graph of Average Deficit/Surplus Power at each hour of the day
- Figure 4.17 Average Daily Energy Curve for Hybrid Design II

**Code:** The code for hybrid (wind and solar) power generating system is as follows:

```matlab
% Example code for Hybrid Design I

time=[1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24];
Power_demand=[1.4 1.2 1.2 1.25 1.3 1.6 2 2.8 2.5 2.2 2.2 1.8 1.75 1.7 1.6 1.6 1.8 2.4 2.6 2.65 2.5 2.45 2.25 1.7];
solar=[0 0 0 0 0 .08 .15 .3 .38 .53 .6 .67 .75 .59 .5 .41 .34 .2 .1 .09 0 0 0];
```

```matlab
end
```
wind=[3.4 3.3 3.2 3.4 3.2 3.5 3.2 3.2 3.6 3.4 3.8 4.77 5 5.2 5.7 5.75 5.5 4.5 4.1 4.2 3.9 3.8 3.7 3.6];

p=.5*1.225*.95*.3*38.48;

for in=1:24
    Power_wind(in)=p*wind(in)*wind(in)*wind(in)/1000;
end

for i=1:150
    Power_solar=.12*1.07*i*solar;
    j=2
    total_power=j*Power_wind+Power_solar;
    Defecit(i)=mean(total_power-Power_demand);
end

subplot(1,3,1)
plot(Defecit)

temp=find(Defecit>0);
a=temp(1);
Power_solar = .12 * 1.07 * a * solar;

total_power = Power_wind + Power_solar;

Deficit_a = (total_power - Power_demand);

subplot(1,3,2)
plot(Deficit_a)

temp = 0;
temp(1) = Deficit_a(1);
temp(2) = Deficit_a(2) + Deficit_a(1);

% temp(2) = deficit(2) + temp(1)

for in = 3:24
    temp(in) = temp(in - 1) + Deficit_a(in);
end

integrate_deficit = temp

subplot(1,3,3)
plot(integrate_deficit)
Chapter 5
COST OPTIMIZATION

After calculating the size of the three designs, cost needs to be considered to find the most economic design. Levelised cost of energy is an indicator that decides the optimal design with the lowest cost. A diesel generator has been considered in all the cases in order to receive electricity when battery is low on charge.

Below are the generalized equations used for all the four cases [16]

\[ LCE = \frac{TPV \times CRF}{E_{load}} \quad (I) \]

\[ TPV = C_{pv} + C_{wind} + C_{bat} + C_{gen} \quad (II) \]

\[ CRF = \frac{i(1+i)^n}{(1+i)^n - 1} \quad (III) \]

Where,

- \( TPV \) = Total present value of all components
- \( CRF \) = Capital Recovery Factor
- \( LCE \) = Levelised cost of energy
- \( E_{load} \) = Total yearly load in KWh
- \( i \) = annual discount rate
- \( n \) = system life in years
- \( C_{pv} \) = present value of capital and maintenance cost of PV panels in system life
Cwind = present value of capital and maintenance cost of wind turbines in system life

Cbat= present value of capital and replacement cost of battery bank in system life

Cgen = cost of the diesel generator

Summing the output power generated by a single solar panel from Figure 4.3 we get the total power generated by a single PV panel per day i.e. 0.73 KWh.

Summing the output power generated by a single wind turbine from Figure 4.5 we get the total power generated by a single wind turbine per day i.e. 16.06 KWh.

5.1 CASE I: Solar Alone

The following has been considered/calculated from graphs. [16]

n=20 years
i=6%

No of PV panels = 64
PV system life = 20 years
No of batteries = 23
Battery life = 4 years
Battery replacement factor = 20/4=5
Maintenance cost = 1% of the capital cost = $393
Balance of system cost = 50% of the cost of PV module = $1.5
Diesel Generator cost (Cgen) = $2000

\[ E_{load} = 0.73\text{KWh PV generated/panel/day} \times 64 \text{PV panels} \times 365 \]

Therefore using the above values, Table 5.1 & 5.3 we get,

1. CRF = 0.08
2. TPV = \( C_{pv} + C_{bat} \)
   \[ = (64\text{panels}) \times ($614/\text{panel}) \times (1.5) + $393 + (23\text{batteries}) \times ($225/\text{battery}) \times (5 \text{installments}) + $2000 \]
   \[ = $85,212 \]
3. LCE = $0.41/ KWh

5.2 CASE II: Wind Alone

The following has been considered / calculated from graphs [16]

n=20 years
i=6%
No of wind turbines = 3
Wind Turbine life = 20 years
No of batteries = 15
Battery life = 4 years

Battery replacement factor = 20/4=5

Maintenance cost= 5% of the capital cost = $ 1500

Balance of system cost = 25% of the cost of PV module=1.25

Diesel Generator cost (Cgen) = $ 2000

Eload = 16.06 KWh wind/day * 365

Using above values, Table 5.2 & 5.3 we get,

1. CRF = 0.08

2. TPV = Cpv + Cbat
   
   = (3windturbines) ($20000/turbine) (1.25) + $1500 + (15batteries) ($225) (5)
   
   = $ 93,375

3. LCE = $ 1.30/ KWh

5.3 CASE III: Hybrid 1st iteration

The following has been considered / calculated from graphs [16]

No of wind turbines = 1

No of PV panels = 47

No of batteries = 21

Diesel Generator cost (Cgen) = $ 2000

PV Panel yearly load = 0.73KWh * 47panels * 365days
Wind Turbine yearly load = 16.06KWh * 365days

Using above values, Table 5.1, 5.2 & 5.3 we get,

1. CRF = 0.08

2. TPV = Cpv + Cbat + Cgen

   = (47) (614) (1.5) + 288 + (1) (20000) (1.25) + 1500 + (21) (225) (5) + 2000

   = 95,700

3. LCE = $ 0.41 / KWh

5.4 CASE IV: Hybrid 2nd iteration

The following has been considered / calculated from graphs [16]

No of wind turbines = 2

No of PV panels = 31

No of batteries = 18

Diesel Generator cost (Cgen) = $ 2000

PV Panel yearly load = 0.73KWh * 31panels * 365days

Wind Turbine yearly load = 16.06KWh * 365days

Using above values, Table 5.1, 5.2 & 5.3 we get,

1. CRF = 0.08

2. TPV = Cpv + Cbat + Cgen
= (31) (614) (1.5) + 190 + (2) (20000) (1.25) + 3000 + (18) (225) (5) + 2000

= $ 103,991

3. LCE = $ 0.58 / KWh

5.5 Result

<table>
<thead>
<tr>
<th>Design</th>
<th>Levelised Cost of Energy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar Alone</td>
<td>$ 0.41 /KWh</td>
</tr>
<tr>
<td>Wind Alone</td>
<td>$ 1.39 /KWh</td>
</tr>
<tr>
<td>Hybrid Design I</td>
<td>$ 0.41 /KWh</td>
</tr>
<tr>
<td>Hybrid Design II</td>
<td>$ 0.58 /KWh</td>
</tr>
</tbody>
</table>

Table 5.1 Result of Economic Analysis
Chapter 6

CONCLUSION

From the above results we conclude that for this case study, a solar alone or the hybrid design I would make sense rather than installing the wind alone design or hybrid design II. The algorithm was designed to find the optimum size of the solar panels and wind turbines. It also calculated the amount of storage required to meet the required load demand. This analysis can be used at any location to decide the optimal sizing of a power plant for standalone installations. An economical analysis was also done in order to find the most economic design.
REFERENCES


[5] Author: Peter Meisen

Title: Overview of Renewable Energy Potential of India


[6] http://www.eia.doe.gov/cabs/India/Full.html Date: 05/03/2010


[8] http://www.mrsolar.com/content/remote-solar-cabins.php Date: 05/03/2010


Title: Unit sizing and cost analysis of stand-alone hybrid wind/PV/fuel cell power generation system
http://www.sciencedirect.com/science?_ob=ArticleURL&_udi=B6V4S-4HCDJN3-1&_user=521814&_coverDate=08/31/2006&_rdoc=1&_fmt=high&_orig=search&_sort=d&_docanchor=&view=c&_searchStrId=1304944432&_rerunOrigin=google&_acct=C000059575&_version=1&_userid=521814&md5=d0eba20a72bc4f597060bf4b9e0da448#eq7 Date: 04/19/2010


[16] Authors: S. Diaf, D. Diaf, M. Belhamel, M. Haddadi, A. Louche
Title: A methodology for optimal sizing of autonomous hybrid PV/wind system
http://hal.archives-ouvertes.fr/docs/00/18/33/57/PDF/diaf_revised.pdf Date: 05/06/2010
