Simulation and Optimization of Wind Turbine, Solar PV, Storage Battery and Diesel Generator Hybrid Power System for a Cluster of Micro and Small Enterprises Working on Wood and Metal Products at Welenchity Site

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Abstract: This thesis presents the design of a hybrid electric power generation system utilizing both wind and solar energy for supplying a cluster of three micro and small enterprises (MSEs) working on wood and metal products at the Welenchity site. The work was begun by investigating wind and solar energy potentials of the desired site, compiling data from different sources and analyzing themusingsoftware. The wind speed and solar irradiation data for the site understudy are collected from the National Metrological Agency (NMA) and analyzed using the software tool HOMER. The results related to wind energy potential are given in terms of the monthly average wind speed, the wind speed PDF, the wind speed CDF, the wind speed DC, and power density plot for the site. Whereas the solar energy potential, has been given in the form of solar radiation plots for the site. According to the results obtained through the analysis, the site has abundant solar energy potential and the wind energy potential is unquestionably high enough to be exploited for generating electric energy using wind turbines with low cut-in wind speed. The design of a standalone PV-wind hybrid power generating system has proceeded based on the promising findings of these two renewable energy resource potentials, wind and solar. The simulations and design has been carried out using the HOMER software. By running the software the simulation results which are lists of power supply systems have been generated and arranged in ascending order according to their net present cost (NPC). Sensitivity variables, such as range of wind speed, solar radiation and diesel price have been defined as inputs into the software and the optimization process has been carried out repeatedly for the sensitivity variables and the results have been refined accordingly.

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The model developed is fairly general and may be adequate for preliminary results for energy consumption cost for MSEs willing to adopt renewable energy sources. Therefore the most economical scenario is using 12 Generic 3kW wind Turbine-12kW PV –20kW Diesel Generator-32 SurretteS6CS25PBattery hybrid system at a selected site.

Keywords: PV-wind hybrid, HOMER, cluster of micro and small enterprises, simulation

1. Introduction

1.1 Background

It is a well-known fact that in many developing countries and less developed countries, a significant proportion of the population lives without usable electrical power. Ethiopia is one of developing countries with more than 80% of its population live without usable electricity [CIA, 2010]. The more noticeable benefits of usable electric power include: improved health care, improved education, better transportation systems, improved communication systems, a higher standard of living, and economic stability. Due to the remote location and the low population densities of the rural communities the traditional means of providing power has proven too expensive, undependable, difficult to maintain, and economically unjustifiable. Consequently, many of these communities remain without electricity and may never receive grid power from the utility. The small town of Welenchity and surrounding communities are one of those rural areas which have no access to electricity. Consequently, a central diesel plant was not considered for micro and small enterprises working on wood and metal products in Welenchity and surrounding area.

The Hybrid Renewable Power Generation System (HRPGS) proposed in this case is a system aimed at the production and utilization of the electrical energy coming from more than one source, provided that at least one of them is renewable [Gupta et. al., 2008]. So far, these vast renewable energy resources are not exploited sufficiently in the country, primarily due to the lack of scientific and methodological know-how as regards planning, site selection, and technical implementation. A further constraint prohibiting their utilization is that the real potential of these resources is not well-known, partly because of the lack of research emphasis in developing these technologies, and partly because of the insufficient resource data base.

Thus, in this thesis a hybrid renewable power generation system integrating these vast solar and wind resources is designed and modeled, to electrify for cluster of micro and small enterprises working on wood and metal products in Welenchity and area surrounding it.

1.2 Objectives

The basic objective of the thesis is to design, and model a stand-alone wind turbine, solar PV, storage battery and diesel generator hybrid Power generation system to investigate alternative power supply options for micro and small enterprises working on wood and metal products around Welenchity villages detached from the main electricity grid and to search for the system which improve the sustainable power supply by replacing existing conventional diesel powered electric supply. More specifically it intended to develop a data base of published data on wind speed and solar radiation of the site, to select a set of photovoltaic modules and wind turbines suitable to generate electricity using the wind and solar resource available in the selected site, propose an optimization procedure to determine the amount and type of PV modules, storage battery and wind turbines needed, under standalone conditions, to satisfy a predetermined demand at minimum cost, perform an economic analysis to compute the net present value of the renewable energy systems propose, conducting an economic evaluation of the systems and compare and propose the best option energy strategies .

2. Methodology

2.1 Data Collection and Pre-processing

Literature reviewincludes reading books, articles, simulation tools and other resources related to the topic are conducted to collect relevant data and information of the site. The data used in this study were obtained from the Ethiopian Meteorological Agency, Ministry of water and energy, Ethiopian Electric Power Corporation (EEPCO) and local MSE working on wood and metal products. The mean of both wind speeds and solar are computed for each month. It should be noted that using monthly wind speed has some limitations such as loosing extremely low or high wind speeds within the month as well as inability to observe diurnal variations in the wind speed. However, using monthly mean wind speed, which is mostly available for most locations, can be used to study the seasonal changes in wind speed and facilitates wind data analysis. Simulation software (HOMER) is developed to analyze the operation of the hybrid system

2.2 Architecture: Hybrid Power Generation System

A hybrid renewable energy system is a system in which two or more supplies from different renewable energy sources (solar-thermal, solar photovoltaic, wind, biomass, hydropower, etc.) with other technologies such as batteries and diesel generator are integrated to supply electricity or heat, or both, to the same demand. The most frequently used hybrid system is the hybrid which consists of Photovoltaic (PV) modules and wind turbines. The most suitable Power Generation and Supply Systems are analyzed and selected. The researcher intensively works on system modeling and simulation includes mathematical modeling of the system and simulating the modeled system using the available optimization software (HOMER). Gradually focus on comparing the cost of electricity produced from renewable energy and the Present cost of fossil fuel (diesel) based electricity generated of site followed by final analysis and interpretation of the results of the findings.

3.Wind Energy Resources and Analysis

3.1. Wind data sources

All renewable energy (except tidal and geothermal power), and even the energy in fossil fuels, ultimately comes from the sun. The sun radiates 174,423,000,000,000 kilowatt hours of energy to the earth per hour. In other words, the earth receives 1.74 x 10 17 W of power [4]. Power production from a wind turbine is a function of wind speed. The relationship between wind speed and power is defined by a power curve, which is unique to each turbine model and, in some cases, unique to site-specific settings. In general, most wind turbines begin to produce power at wind speeds of about 4 m/s (9 mph), achieve rated power at approximately 13 m/s (29 mph), and stop power production at 25 m/s (56 mph).

Table 3.1: Power curve data of the selected wind turbine

S/N	Wind Speed	Power Output
	(m/s)	(kW)
1	0	0
2	3	0
3	4	0.06
4	5	0.11
5	6	0.28
6	7	0.56
7	8	1
8	9	1.56
9	10	2.11
10	11	2.56
11	12	2.83
12	13	2.94
13	14	3
14	15	3
15	16	2.89
16	17	2.67
17	18	2.39
18	19	2.17
19	20	2.06
20	24	2

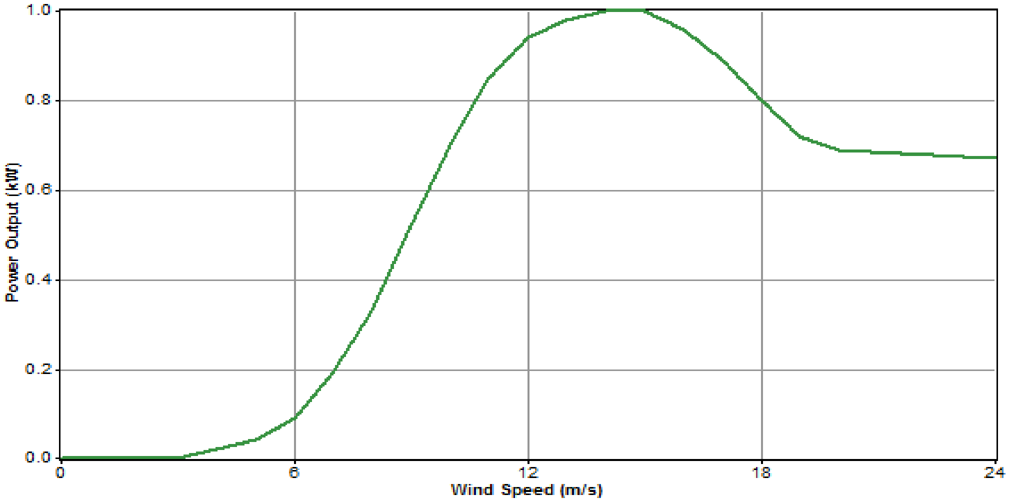

Figure 1.1:Power curve of selected wind turbine

3.2. Wind Turbine Velocities, Distribution, Power, and Energy

The speed of rotation of a wind turbine is usually measured in either rotation speed in revolutions per minute (N in rpm) or angular velocity in radians per second (in rad/s). The relationship between the two is given by:

$$\omega = \frac{2*\pi*R}{60} \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots . . \dots \dots \dots \dots 3.1$$

Another measure of a wind turbines speed is its tip speed which is the tangential velocity of the rotor at the tip of the blades measured in meter per second and it equals to:

$$v = \omega * r \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots .3.2$$

where r is the tip radius in meters.

A non-dimensional ratio known as the tip speed ratio (TSR) is obtained by dividing the tip speed by the undisturbed wind speed, Vo. This ratio which provides a useful measure can be used to compare wind turbines of different characteristics.

$$TSR = \frac{v}{v_o} = \frac{\omega * r}{v_o} \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots 3.3$$

A wind turbine of a particular design can operate over a range of tip speed ratios, but will usually operate with its best efficiency at a particular tip speed ratio. The optimum tip speed ratio for a given wind turbine rotor will depend upon both the number of blades and the width of each blade [5].

A term describes the percentage of the area of the rotor, which contains material rather than air is known as solidity. Wind turbines with large number of blades have high solidity, but wind turbines with small number of narrow blades have low solidity. Multi blade wind pumps have high solidity rotors and modern electricity generating wind turbines (with one, two or three blades) have low solidity rotors. The turbines with low solidity have to turn much faster than the high solidity turbines in order to interact with all the wind passing through. Optimum tip speed ratios for modern low solidity wind turbines range between about 6 and 20 [5].

The energy contained in the wind is its kinetic energy (E_{kin}) and it is equal to [5]:

$$E_{kin} = \frac{1}{2} * m * v^2 \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots 3.4$$

Where (m) is the mass of air in kilograms and (V) is speed of air in meters per second. Mass of air flowing through a certain area (A) per second (m.) is:

$$m^{\cdot} = \rho * A * v \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots . .3.5$$

Whereρ :is the density of air in kilograms per cubic meter.

So, kinetic energy in the wind per second which is equal to power (P) in the wind in watts is equal to:

$$P = \frac{1}{2} * \rho * A * v^3 \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots . .3.6$$

As it is appeared from the power relation above, wind speed (cubic) has a strong influence on power output.

The power contained in the wind is not in practice the amount of power that can be extracted by a wind turbine. This is because losses are incurred in the energy conversion process, also because some of the air is pushed aside by the rotor and by passing it without generating power.

3.3 Wind speed data of the site

The available wind speed measured at Adama (EEPCO's 10 meters station) indicates that wind with minimum speed occurs during August (6.61m/s), while the wind with high velocity occurs during November, December, January and February; 9.95, 10.29, 9.27 and 9.65 m/s respectively. The values calculated over 3 years (2015 to 2017) indicate that mean wind speed is 8.33 m/s. Wind speed at Adama (National Meteorological Service Agency 2 meters station) illustrates that wind with minimum speed occurs during August (1.76), while months which receive high wind speed are November, December and January (2.65, 2.74, and 2.47 m/s respectively). The wind speed at Adama (EEPCO's 40 meters station) shows that a month which gets minimum wind speed is August (6.04) and months of high wind speed are November, December, and January (11.15, 11.05, and 10.56 m/s respectively). Generally, data from all stations show that the wind speed at Adama is high throughout the year but there is decreasing trend during summer months. The wind direction recorded every ten minutes a day in the past three years (2015-2017) indicates that there is seasonal variation of wind direction. However, the prevailing wind direction is Northeasterly.

3.4 Power and energy produced by a wind turbine

A rough initial estimate of electricity production (in kWh / m²/year) at a certain site is [5]:

$$E_{gen} = K_{WT} * (v_{av})^3 \quad \ldots \ldots 3.7$$

Where: E_{gen} is the annual electrical energy generated by a wind turbine (kWh), K_{WT}= 3.2 (kg/m/s) is a factor based on typical turbine performance, and v_{av} is the site average annual wind speed in m/s.

3.5 Effect of height on wind speed

The height at which the speed of wind is measured affects the value of the wind speed. As height increases the speed of wind increases, so it is more valuable to increase the height of wind turbine in respect of power that can be captured, but as height increases the initial capital cost of the tower increases and also the maintenance and operation costs increases, so it is a compromise issue.

So when calculating the output of wind generator, the measured data of average hourly wind speed must be converted to the corresponding values at the hub height.

Knowledge of wind speeds at heights of 20 to 120 m above ground is very desirable in any decision about location and type of wind turbine to be installed. Many times, these data are not available and some estimate must be made from wind speeds measured at about 10 m. This requires an equation which predicts the wind speed at one height in terms of the measured speed at another, lower, height. One possible form for the variation of wind speed u (z) with height z is [3]:

$$V = V_{ref}\left[\frac{\ln\left({}^{z}/_{z_0}\right)}{\ln\left({}^{z_{ref}}/_{z_0}\right)}\right] \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 3.8$$

where: V=wind velocity at height z above ground level

V_{ref}= reference velocity, i.e., a wind velocity at height z_{ref}

Z= height above ground level for the desired velocity V

Z_0= surface roughness length of the site, 0.12 in our case

Z_{ref}= reference height, i.e., the height where the exact wind velocity

V_{ref}= is known as reference velocity

The annual average wind speed at 10m for welenchity site is already known before which is 8.3m/s and the average wind speed at the hub height of 40m with the wind shear exponent of 0.12 is calculated as follows:`

z=40m, z_{ref}=10m, z_o=0.12,V_{ref}=8.3m/s

Hence, the wind speed at the hub height is:

$$V = 8.3\,m/s\left[\frac{\ln\left({}^{40m}/_{0.12}\right)}{\ln\left({}^{10m}/_{0.12}\right)}\right] = 10.904\,m/s$$

3.6Effect of the Average atmospheric pressure

The average atmospheric is used on the annual basis, because the power available from the wind depends upon this value. This value s used to calculate the pressure coefficient adjustment. The average atmospheric pressure is inversely proportional to the altitude. The average atmospheric pressure typically ranges from 60 to 103 KPa. The lower end the range corresponds to a site at an elevation of approximately 4,000 m whereas the higher end of the range corresponds to sea level. The atmospheric pressure at standard condition is 101.3 KPa [Elliot, 1986].

Note that the atmospheric pressure falls with increasing altitude. Up to about 5,000 m altitude, the mean atmospheric pressure, P (KPa), at altitude of Z meters above sea level can be estimated by:

$$P = P_{sealevel} \times e^{\left(-{}^{Z}/_{8200}\right)} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 3.9$$

Where

$P_{sealevel}$ is the atmospheric pressure at sea level of site (i.e., 86.4 KPa)

$$P = 86.4 * e(-60/8200)$$

$$P = 85.8KPa$$

3.7 Effect of annual average temperature

The power available from the wind depends on the annual average temperature. This value is used to calculate the temperature coefficient adjustment. The Greater the temperature, the lower the air density and therefore, the lower the power available from the wind and this relation is shown above on effect of temperature and altitude on air density. Accordingly the mean annual temperature (T_m) of the site is22.4℃.

3.8 Wind Speed Frequency with Rayleigh distribution

The reliability of Weibull distribution in wind system analysis depends on the accuracy in estimating k and c. For the precise calculation of k and c, adequate wind data, collected over shorter time intervals are essential.The existing data may be in the form of the mean wind velocity over a given time period..

Similarly the cumulative distribution function of a wind system is given by:

$$F(V) = \int_{0}^{\infty} f(V)\, dv = 1 - e^{-\left({V}/{c}\right)^{k}} \text{ -------------------- }3.10$$

3.9 Rayleigh Approach for Energy Estimation of wind systems

In addition to the mean wind speed, the other two significant wind speeds for wind energy estimation are the most probable wind speed (V_F) and the wind speed carrying maximum energy (V_E) [6,12]. Prior studies have shown that wind turbine system operates most efficiently at its rated wind speed. Therefore, it is required that the rated wind speed and the wind speed carrying maximum energy should be as close as possible [16].

Considering Rayleigh distribution, wind energy density at Welenchitysite is given by:

$$E_D = \left({3}/{\Pi}\right) \rho_a V_m^3 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 3.11$$

Energy available at Welenchitywind power system site for the unit area of the rotor, over a time period, can be estimated using the expression:

$$E_t = TE_D = \left({3}/{\Pi}\right) T \rho_a V_m^3 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 3.12$$

The most frequent wind velocity at the Welenchitywind power system site$V_{Fmax}$is given by:

$$V_{FMax} = \sqrt[2]{\left({2}/{\Pi}\right)}\, V_m \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 3.13$$

The velocity contributing maximum energy to Welenchitywind energy system is determined from:

$$V_{EMax} = 2 \times \sqrt[2]{\left({2}/{\Pi}\right)}\, V_m \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 3.14$$

4.Solar Energy Resources and Analysis

4.1Solar data sources

Sunshine hour data during a year are very important and essential for design and sizing of PV power systems. Solar radiation measurements in addition to temperature measurements are necessary to calculate the output power of the PV system. Solar radiation and temperature measurements shall be available on hourly basis to be used by the simulation program for the evaluation process. For Welenchity site the temperature measurements are not available, so due to their almost similar latitude, data from Adama can be used for simulation program to evaluate feasibility of the site. Accordingly, the daily average sunshine hour of Welenchity site from 2015-2019 will be shown in the following table:

Table 3.5: Monthly average of daily sunshine hour for Welenchity site (Adama) [2]

Month		Jan	Feb	Mar	Apr	May	June	Jul	Aug	Sept	Oct	Nov	Dec
Average of daily sunshine hour per year	2015	10.4	9.6	9.7	8.4	8.9	7.7	6.5	6.9	5.5	6.7	7.8	8.6
	2016	7.9	7.4	7.7	8.7	10.1	7.8	7.2	7.6	7.9	8.8	9	6.2
	2017	7.8	6.5	8.6	8.7	7.2	7.6	6.1	8.8	7.5	9.5	9.4	10.4
	2018	9.5	8.9	7.5	7.6	9	7.9	6.5	5.9	7.4	7.3	9.9	8.6
	2019	9.2	8.7	9.2	8.3	8.8	7.6	7.6	6.4	6.5	6.3	9.3	10.6
Monthly average of daily sunshine hour		8.96	8.22	8.54	8.34	8.8	7.72	6.78	7.12	6.96	7.72	9.08	8.88

Table 3.6: Monthly average of daily solar radiation for Welenchity site (Adama) [2]

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
Monthly average of daily sunshine hour	8.96	8.22	8.54	8.34	8.8	7.72	6.78	7.12	6.96	7.72	9.08	8.88
Daily Solar radiation @Lat = 8.468O N and Lon = 39.159O E	6.24	6.5	6.66	6.56	6.51	5.88	5.3	5.31	5.9	6.41	6.28	6.07

These figures which are the main inputs for the software are relatively high and very encouraging to use as a PV for electrification for the selected site.

4.2 Analysis of Photovoltaic (PV) Power for the Selected Site

To determine the PV electricity generation potential for a particular site, it is important to assess the average total solar radiation received over the year. Ethiopia is one of the developing countries which have no properly recorded solar radiation data and, like many other countries, what is available is sunshine duration data. However, given a knowledge of the number of sunshine hours and local atmospheric conditions, sunshine duration data can be used to estimate monthly average solar radiation, with the help of empirical equation 3.15 [Duffie and Beckman, 2006].

$$H = \bar{H}_O\left(a + b\left(\frac{\bar{n}}{N}\right)\right) \ldots\ldots\ldots\ldots 3.15$$

where H is the monthly average daily radiation on a horizontal surface (MJ/m2), $\bar{H}_O$is the monthly average daily extraterrestrial radiation on a horizontal surface (MJ/m2), $\bar{n}$is the monthly average daily number of hours of bright sunshine, N is the monthly average of the maximum possible daily hours of bright sunshine, a and b are regression coefficients Solar radiation, known as extraterrestrial radiation, $\bar{H}_O$, on a horizontal plane outside the atmosphere, is given by equation 3.2.

$$H_o = \frac{24 * 3600 * G_{sc}}{\pi}\left(1 + 0.033 * \cos\left(\frac{360 n_d}{365}\right)\right) * \left(cos\emptyset cos\delta sin\omega_s + \frac{\pi\omega_s}{180}\right) sin\emptyset sin\delta \ldots\ldots\ldots\ldots 3.16$$

Where $n_d$is the day number, $G_{sc}$is the solar constant (1367 W/m^2), $\emptyset$ is the latitude of the location (°), δ is the declination angle (°),which is the angular position of the sun at solar noon, with respect to the plane of the equator and its value in degrees is given by Cooper's equation [11]:which is given as follows:

$$\delta = 23.45 \sin\left(248 + n_d\left[\frac{360}{365}\right]\right) \ldots\ldots\ldots\ldots 3.17$$

The solar hour angle (ω_s) is the angular displacement of the sun east or west of the local meridian; morning negative, afternoon positive. The solar hour angle is equal to zero at solar noon and varies by 15 degrees per hour from solar noon. The sunset hour angle s w is the solar hour angle corresponding to the time when the sun sets and it is given by:

$$\omega_s = \cos^{-1}(-tan\emptyset tan\delta) \ldots\ldots\ldots\ldots 3.18$$

The maximum possible sunshine duration N is given by

$$N = \frac{2}{15}\omega_s \ldots\ldots\ldots\ldots 3.19$$

Equations (4.1) and (4.5) are used to calculate the daily extraterrestrial radiation and the maximum possible daily hours of bright sunshine respectively at the specified location. The regression coefficients a and b for M number of data points can be calculated from the following equations (4.6) and (4.7) respectively [Getachew, 2009].

$$a = \frac{\sum \frac{\bar{H}}{H_o} \sum ((\frac{\bar{n}}{\bar{N}})^2) - \sum \frac{\bar{n}}{\bar{N}} \sum \frac{\bar{n}}{\bar{N}} \frac{\bar{H}}{H_o}}{M \sum (\frac{\bar{n}}{\bar{N}})^2 - (\sum \frac{\bar{n}}{\bar{N}})^2} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 3.20$$

$$b = \frac{M \sum \frac{\bar{n}}{\bar{N}} \frac{\bar{H}}{H_o} - \sum \frac{\bar{n}}{\bar{N}} \sum \frac{\bar{H}}{H_o}}{M \sum (\frac{\bar{n}}{\bar{N}})^2 - (\sum \frac{\bar{n}}{\bar{N}})^2} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 3.21$$

Results estimated in this way are compared with the data which are obtained from sources such as NASA's surface solar energy data set or the SWERA global meteorological database. Drake and Mulugetta developed sets of constants a and b for various locations in Ethiopian [Drake and Mulugetta, 1996]. In this thesis, regression coefficients developed in their work was used.

4.3 Wind Turbine Modeling and Sizing

The power output of a wind turbine is determined by
its power curve and the instantaneous wind speed at the sight of installing this wind turbine. A mathematical model for the power curve of a wind turbine taking into account these parameters is as follows [19]:

$$P_W = \begin{cases} 0 \\ a * v^3 - b * P_r \\ P_r \end{cases} \begin{cases} V < V_{ci} \\ V_{ci} < V < V_r \\ V_r < V < V_{co} \end{cases} \text{ and } 0 \text{ for } V > V_{co}. 4.1$$

Where, P_W(in W/m2): is the output power density generated by a wind turbine,

$$a = \frac{P_r}{V_r^3 - V_{ci}^3} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 4.2$$

$$b = \frac{V_{ci}^3}{V_r^3 - V_{co}^3} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 4.3$$

and ,P_r,V,V_{ci},V_r,V_{co},are rated power (w) , instantaneous , cut-in , rated and cut-out wind speeds in (m /s) respectively.

The real electrical power delivered is calculated as

$P_{wout} = P_w * A_w * \eta_w \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots$ 4.4)

whereAw is the total swept area of the wind turbine in $m^2$and $\eta_w$is the electrical efficiency of the wind generator and any other electrical components connected to the generator.

4.4 PV Panel Modeling and Sizing

The total peak power of the PV generator required to supply certain load depends on load, solar radiation, ambient temperature, power temperature coefficient, efficiencies of solar charger regulator and inverter and on the safety factor taken into account to compensate for losses and temperature effect. This total peak power is obtained as follows:

$$P(r-pv)=\frac{EL}{(\eta PVR*\eta V*PSH)}*S_F\ \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots..4.5$$

WhereE_L is the daily energy consumption in kWh, PSH is the peak sun hours (in Welenchity case PSH = 9.08) and as a figure it represents the yearly average of daily solar radiation intensity on horizontal surface in (kWh/m^2 / day),η_{PVR},η_V are efficiencies of solar charger regulator and inverter and $S_F$is the safety factor.

4.5 Battery Bank Modeling and Sizing

When the power generated from the renewable system (wind and PV in the case under study) exceeds the load requirement, energy is stored in the battery. A minimum storage level is specified for a battery so that should not be exceeded it. This level is a function of battery DOD so that

$$Emin=E_{BN}*(1-DOD)\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots4.6$$

where

E_{min}:minimum allowable capacity of the battery bank,

E_{BN}: is the nominal capacity of battery bank,

DOD: is the depth of discharge.

Energy stored in the battery at any time during charging mode can be expressed as [3]:

$$E_b(t)=E_b(t-1)*(1-\alpha)+\left[E_w(t)+E_{PV}(t)-\frac{E_L(t)}{\eta_v}\right]*\eta_{wh}\dots4.7$$

Energy stored in the battery at any time during discharging mode can be expressed also as [3]:

$$E_b(t)=E_b(t-1)*(1-\alpha)-\left[\frac{E_L(t)}{\eta_v}\llbracket-(E\rrbracket_w(t)+E_{PV}(t))\right]\dots\dots4.8$$

where

α : is hourly self-discharge rate,

$E_{w(t)}$: is the energy from wind turbine during the time interval,

$E_{pv(t):}$ is the energy from PV system during the time interval,

E_L(t:)is the load requirement during the time interval

E_b(t) and E_b(t-1): are the charge capacity of battery bank at the time t and (t-1) respectively,

$\eta_v$and η_{wh} : are the efficiency of inverter and battery bank respectively as stated before.

4.6 Battery bank sizing

The two types of lead-acid batteries available at high capacities are the regular and the block types. The block type has long life time (>10 years), high cycling stability-rate (> 1000 times) and capability of standing very deep discharge, but has higher price than regular batteries [1].

The ampere-hour capacity (CAh)and watt-hour capacity (CWh)of a battery bank required to supply a load for a certain period (day) when an energy from renewable resources is not available can be specified as follows [1] :

$$C_{Wh}=\frac{E_L*AD}{\eta_v\ *\ \eta_{wh}*DOD}\dots\dots\dots\dots\dots\dots\dots.\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots4.9$$

Where AD: is the daily autonomy.

It is obvious from relation (4.9) that total capacity of the battery depends on daily autonomy which represents number of days that battery will be capable to supply the load in case of shortage of the renewable sources.

4.7Diesel Generator Ratings and sizing

Diesel generator is used in the system for following tasks: To supply load when the output power from wind and PV is not enough to operate this load, as well as to bring the SOC of batteries to an acceptable level. The Diesel generator rating shall be large enough to achieve these tasks. Optimal unit sizing of a Diesel generator requires careful consideration of several factors including detailed analysis of daily and seasonal load fluctuations, annual load growth, and incorporation of practical constraints for feasible and reliable Diesel operation.. The reason is that remote community loads are normally characterized as being highly variable, with the peak load as high as many times the average load [9].

The Diesel generator should be selected to cover the load so its ratings are determined according to load specifications. The optimum selection of the generator rating is such that the generator with other sources shall provide load with power it needs at all cases. A practical approach for large loads is to employ multiple units, e.g. a set of two or three Diesels, with various sizes and apply a Diesel cycling and dispatch strategy to optimize the loading of each unit to achieve maximum fuel efficiency.

4.8 Charge Controller (Regulator) Modeling and Sizing

Charge controller is an essential component in hybrid systems where a storage system is required. It protects battery against both excessive overcharge and deep discharge. Charge controller shall switch off the load when a certain state of discharge is reached, also shall switch off battery from the DC bus when it is fully charged. Charge controller can be adjusted to deal with different charge and discharge conditions. Charge controller act as interface between each of wind turbine and PV panel and the DC bus where the battery is connected. So charge controller is modeled by its efficiency where its output is

$$P_{WR} = P_{Wout} * \eta_{WR} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots .4.10$$

And

$$P_{PVR}=P_{PV\ out}*\eta_{PVR}\dots\dots\dots\dots\dots\dots 4.11$$

where

P_{WR}: is the output power of the wind charge controller,

P_{Wout}: is the wind turbine output power,

H_{WR}: is the efficiency of the wind charge controller,

P_{PVR}: is the output power of the PV charge controller,

P_{pvout}: is the PV panel output power, and

η_{PVR}: is efficiency of the PV charge controller.

The charge controller ratings are chosen according to the battery voltage and the output power from each of wind turbine and PV panel.

4.9 Bidirectional Inverter Modeling and Sizing

A bidirectional inverter is essential in the hybrid system where a storage system and a backup Diesel generator are involved in the system. It can transfer power simultaneously in both directions. The inverter can supply DC and charge the batteries so it provides a path from the AC bus to the DC bus, in this case it acts as rectifier circuit which changes AC Diesel generator voltage to DC voltage. In the other way, it provides path from DC bus to the AC load so it acts as an inverter which changes DC voltage to AC voltage needed by the load.

Shape of the output waveform, power rating and efficiency are the parameters that shall be considered to choose a certain bi-directional inverter for certain application.

In a charger (rectifier) mode a bidirectional inverter can be modeled as follows:

$$P_{dicm} = P_{Gout} * \eta_{dicm} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots . \dots\dots .. 4.12$$

Where

P_{dicm}: is output power of bidirectional inverter in its charge mode,

P_{Gout}: is Diesel generator output power, and

η_{dicm}: is the efficiency of bidirectional inverter in its charge mode.

In this mode of operation (charger mode) the charger is characterized by its nominal AC voltage and voltage range, nominal DC output voltage that shall matched with DC bus voltage and it's charging current.

In an inverter mode a bidirectional inverter can be modeled as follows:

$$P_{invm} = P_{DCB} * \eta_{invm} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots 4.13$$

Where

P_{invm}: is output power of directional inverter in its inverter mode,

P_{DCB}: is the DC bus power

η_{invm}:is efficiency of bidirectional inverter in its inverter mode (usually equals the efficiency of bidirectional inverter in its rectifier mode(η_{dicm}) and thus calledη_{V}.

In this mode of operation (inverter mode) an inverter is characterized by its nominal voltage and voltage range that shall be matched with the DC bus voltage, nominal output voltage and its output power that shall fulfill the load power.

The efficiency of converting the direct current to alternative current of most inverters today is 90% or more [Rivera, 2008]. Many inverters claim to have higher efficiencies but for this thesis the efficiency that was used is 90%.

5. Simulation Software and Results

5.1 Simulation Approach

HOMER performs three principal tasks: simulation, optimization, and sensitivity analysis based on the raw input data given by user. In the simulation process, the performance of a particular power system configuration for each hour of the year is modeled to determine its technical feasibility and

NPC. In the optimization process, many different system configurations are simulated in search of the one that satisfies the technical constraints at the lowest NPC. In the sensitivity analysis process, Sensitivity analysis helps assess the effects of uncertainty or changes in the variables over which the designer has no control, such as the average wind speed or the future fuel price.

The system simulation is performed by considering the system reliability as 100%, so no interruption is assumed during operation of the system. In this approach the renewable energy sources (wind & PV) plus the energy stored in the battery are used to cover the demand. The diesel generator is switched on as a back-up source when the battery is discharged to a certain level. The following cases will be considered with the illustrated priority while developing the simulation software:

Case1: Sufficient generated energy by renewable sources (wind & PV).The use of this energy to supply load has priority over using batteries or diesel generator. The extra energy is used to charge batteries.

Case 2: As case 1 but surplus energy is generated by the system greater than the need to supply the load and the batteries. In this case the surplus energy is consumed by the dump load.

Case 3: The generated energy by the renewable sources is not sufficient to supply the load. The priority here is to use the stored energy in the batteries in addition to the generated energy by the renewable sources rather than operating the diesel generator.

Case 4: The generated energy by the renewable sources is not sufficient to cover the load demands and the battery is also discharged to its minimum value. In this case the diesel generator is switched on, and in addition to the generated energy by the renewable sources, it supplies the load and charge the batteries. The hybrid systems still in this mode of operation until the batteries are recharged to their full capacity.

5.2 Software Inputs and Outputs

Wind speeds input to the program shall be corrected to take into account the height of the wind turbine tower. In addition to this, solar radiation input to the simulation program is measured on a horizontal plane and shall be corrected to take into account the tilted and azimuth angles of the tilted modules. Simulation program shall do that. In addition to numerical results, graphs of different variables can be obtained.

5.3 Optimization results

The monthly average wind speed of the site together with other related data, such as values of Weibull parameter k, diurnal pattern, autocorrelation, etc, was fed into HOMER. After entering the wind and solar resource data into software, to find the optimum solutions, HOMER is run repeatedly by varying parameters that have a controlling effect over the output.In addition to those input parameters, multiple prices of diesel oil and PV modules have been used for sensitivity analysis. The output of the simulation is a list of feasible combinations of PV, wind-turbine, generator, converter, and battery hybrid system set-up.

The following remarkable results can be noted from optimization conducted. The most cost effective system, i.e. the system with the lowest net present cost, is the one with PV-wind turbine-generator-battery converter set-up with the generator operating under a load following (LF) strategy (a dispatch strategy whereby the generator operates to produce just enough power to meet the primary load; lower-priority objectives, such as charging the battery bank or serving the primary load, is left to the renewable power sources). For this set-up, the total net present cost (NPC) is 13282244.8 Birr, the cost of energy (COE) is 10.14024/kwh, contribution from renewable resources is 85%, the amount of diesel oil used annually is 10,463 liters and the generator operates for 2701 hours per year.

In this set-up the part that renewable resources contribute to the supply system is quite significant, being 85%. Therefore this setup could be a good choice for implementation.

The second most cost effective system which comprises Wind-Gen-Battery-Converter set-up is the system in the 2rd row. For this set-up the contribution made by renewable resources is 80 %, which is less than the earlier set-up by 5 %. Nonetheless, the NPC has increased to $ 791,230 and the COE to 0.605 $/kWh. This could also be a good choice if there is a motive for utilizing the available wind energy, which would, however, be at the cost of a 26.3 % increase in the total NPC.

In general we can see in the list numerous feasible setups with different levels of penetration into the renewable resources; the selection, however, depends on whether the initial cost is the principal concern or the benefits gained from utilizing the renewable resources.

5.4 Sensitivity Analysis

Sensitivity analysis was also carried out and for a fixed average wind speed of 8.24 m/s (measured at 10 meters) and average solar radiation of 6.13 kWh/m2/day an increase in diesel price will increase the Net present cost of the system. In the figure, the net present cost of the most cost-effective set-up for a particular set of diesel and PV prices is also included.

The wind turbine used in the design of the system is one with small cut-in wind speed, 2m/s, and also have small capital cost when compared to majority of turbines in the market. Let’s see effects of varying diesel prices as follows:

In this study the parameters which have a controlling effect on the hybrid system under consideration are:diesel price($1.1,$1.2,$1.3), wind speed (6,7.28,9 m/s) and solar Radiation (4.5,5.13,6 kWh/m2/d)

The result of sensitivity analysis indicates that though the optimum system configuration changes under different diesel price assumptions, the hybrid system remains most economically feasible solution than the existing arrangements (diesel-only), under all scenarios considered.

In this case it is observed also that for a diesel price of less than $1.1/L Wind/Generator/Battery/Converter systems is favorable while for diesel price higher than $1.1/L Wind/PV/Generator/Battery/Converter system is favorable .

More generally the modeled hybrid system using wind, solar PV, diesel generator as backup system, and a battery as a storage shall:

Satisfy the load demands for MSEs of the site (281kWh/d),

- ✓ Minimize the net present costs (from 39,762,857 birr to 13,282,245 birr),
- ✓ Minimize cost of energy (from 30.36561 Birr/kWh to 10.14024)
- ✓ Maximize the utilization of renewable sources (from 0% to 84%),
- ✓ Reduce the environment pollution emissions from diesel generator (from 117,304 ton/year to 27,553 ton/yr

6. Conclusions

The results obtained from the software give numerous alternatives of feasible hybrid systems with different levels of renewable resources penetration which their choice is restricted by changing the net present cost of each set up. The COE of the feasible setups in this study is high compared to the current global electricity tariff and the tariff in the country. However, considering the shortage of electricity in the country (<20% coverage) and absence of electricity usage in rural areas (<2% coverage), this cost should not be taken as a decisive factor. At current costs, central grid power is the least expensive option but will not be available to most rural households.

Qualitatively, the selected standalone hybrid system shall play a great role in protecting the environment from degradation, the improvement of life of people living in rural area, development of clean energy, the future situation regarding fossil fuel sources, and its contribution to the reduction of pollutant emissions into the environment should be taken in to account. Taking these issues into account the free solar and wind energy of the country should be utilized to improve the quality of life of the MSEs living in rural areas.

Quantitatively, as per simulation results, the following conclusions can be demonstrated:

- ➢ Usingwind, PV, diesel with a storage battery bank hybrid system to supply a load, a combination of them with wind as a main source, with limited operation of diesel generator (2,701 hour/year) forms the optimum case with a COE equals to 10.14024 Birr/kWh.
- ➢ Using wind as a standalone system to supply load is not economical or practical choice because of low availability of wind during different times in a year (months from September to December have low average wind speeds). Higher rating is required for the wind turbine required to supply a load with a certain power, also higher battery capacity (higher autonomy days) are required to supply this load.
- ➢ Using PV as a standalone system to supply the load isn't also economical or practical one. Different times through a year have low solar isolation especially during winter months (Months December, January, and February).
- ➢ Using diesel generator only to supply the load requires many units to supply this load, more fuel, so more CO2 is produced, also more maintenance and operational costs is needed. The COE is high; it is 30.36561 Birr/kWh and it is to high compared hybrid system (10.14024 Birr/kWh). Amount of CO2 produced is about 117,304/year, it is too high compared with the hybrid (27,553/yr).
- ➢ A wind-solar cell hybrid energy system would be cost effective if there is reduction in component cost by installation of many of this hybrid system in a farm thereby lowering the investment cost

per kilowatts. Its availability, sustainability and environmental friendliness make it a desirable source of energy supply.

- Though the optimum system configuration changes under different diesel price assumptions, the hybrid system remains most economically feasible solution than the existing arrangements (diesel-only), under all scenarios considered.
- From the value of NPC and COE, it is observed that using Wind only is economically preferred on using PV wind only. But comparing these two cases with the base case where hybrid wind-PV-diesel system is analyzed, the base case is economically preferred
- On the other hand using both Wind,-Storage Battery -Diesel Hybrid System (without PV) and PV-Storage Battery - Diesel Hybrid System (without wind) is also not an economical because their corresponding NPC is too high (in million Dollars) as compared to the selected hybrid system under consideration
- Comparing .hybrid system with set up of wind Turbine, Solar PV, Storage Battery and Diesel Generator with hybrid system including Wind-PV set up, from NPC point of view the latter combination is preferable .However, due the variability of wind speed and solar radiation throughout different months of a year at a selected site and to supply a reliable and sufficient power for MSEs working on wood and metal products the former hybrid system is the best choose for implementation.
- Hence, the model developed is fairly general and may be adequate for preliminary results for energy consumption cost for MSEs willing to adopt renewable energy sources. Therefore the most economical scenario is using wind-PV –Diesel Generator-Battery hybrid system.

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