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Wind And Photovoltaic Thermal Power Production For Lift Irrigation

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Abstract:
The main objective of this study is to show the ground-water sources for full year farming and avoiding idle time by using wind and photovoltaic thermal (PVT) hybrid water pumping system for irrigation application and its viability.
Unlike the previous optimization procedure which only consider the demand for hydraulic energy; this paper presents all the relevant system elements and their characteristics will be analyzed. The system elements are wind and Photovoltaic thermal power production for water pumping system, climate and variation of total head, soil, crops types and irrigation method. All this have directly influence on the demand load for water pumping and it enables us to find the optimal power required for water pumping systems. Also by using photovoltaic thermal power production rather PV modules alone, increased by maintaining the temperature of the modules. The paper approaches through mathematical modeling and use Microsoft Excel with combination of MATLAB program for simulation. In the simulation program the water pumping system elements and their relation are integrated and the optimal nominal electric power generated by the selected hybrid system is generate the required energy of 2831.7kWh/year . It was concluded that the hybrid system is viable with economic background evaluated depend on Net Present Value (NPV), Internal Rate of Return (IRR); Benefit Cost ratio (B/C), and payback period; which results $3409.57, 9%, 1.8 and 5 year respectively.

***Key words**: Hybrid, PVT, Optimization, Techno-economic*

1.Introduction

Rural areas in Ethiopia are characterized by either low-density settlement with relatively large distances between households, or villages with fewer inhabitants. This has hindered the use of modern sources of energy. Leaving rural inhabitants, to continue on the course of the current use pattern of traditional energy sources, is bound to have highly negative consequences for the rural economy at large, as well as the environment and the ecosystem balance. Fortunately, the natural resource base for the generation of modern sources of energy is plenty. There are also favourable economic, environmental and energy policies.

Most of the developing country is depending only on the rain for the farming since the rural areas where other energy likes electricity, diesel is not economically viable. Although lack of modern technology lags behind the farmer of the region to arrive at an expected development. Wind and PV hybrid system could be used to transform the fortunes of the rural poor and also the country's economy. Because of wind/ solar powered technologies, last longer and entail none or very little recurrent cost, poor rural communities would find it more suitable for their needs.

Over the present year’s hybrid technology has been developed and upgraded its role in renewable energy sources while the benefits it produces for power production can't be ignored and have to be considered. Nowadays many applications in rural and urban areas use hybrid systems. Many isolated loads try to adopt this kind of technology because of the benefits which can be received in comparison with a single renewable system.

2.Site And Data Description

The town of Debre Berhan is located at 09041’N latitude and 39031’E longitude, 130 km from Addis Ababa on the main road Addis Ababa-Dessie–Mekele road in the Amhara region, north shoa administrative zone. Debre Berhan is situated on a plateau in the central Ethiopia highland system about 15km west of the great rift escarpment.

Debre Berhan lies between an elevation of 2800 and 2845m a.s.l. From the elevations it belongs to the dega climatic zone. The mean annual temperature ranges between 5^0C and 23^0C. The mean annual precipitation is 874mm. The wind data were normalized to 25m height using the 1/7th wind power law. The quadratic and the linear Angstrom regression equations have been used to calculate the monthly average values of solar radiation from the sunshine hour.

3.Modeling Of Hybrid Water Pumping System

The hybrid water pumping system consists of wind turbine, PV array, the direct current (DC) motor and the pump.

3.1.Wind Turbine Modeling And Simulation

There are three main factors which determine the power output of a whole wind energy conversion system i.e., the power output curve (determined by aerodynamic power efficiency, mechanical transmission efficiency and converting electricity efficiency of generator) of a chosen wind turbine, the wind speed distribution of a selected site where the wind turbine is installed, and the hub height of the wind tower. Choosing a suitable model is very important for wind turbine power output simulations.

A mathematical model for the power curve of a wind turbine taking into account these parameters is as follows the equation 1-5.

$$P_W = \begin{cases} 0 & \mathrm{V} < \mathrm{V_{ci}} \\ a*V^3 - b*P_r & \mathrm{V_{ci}} < \mathrm{V} < \mathrm{V_r} \\ P_r & \mathrm{V_r} < \mathrm{V} < \mathrm{V_{co}} \\ 0 & \mathrm{V} > \mathrm{V_{co}} \end{cases} \qquad (1)$$

Where

P_W in (W/m^2) is the output power density generated by a wind turbine,

$$a = \frac{P_r}{V_r^{\ 3} - V_{ci}^{\ 3}} \quad \text{and} \quad b = \frac{V_{ci}^{\ 3}}{V_r^{\ 3} - V_{ci}^{\ 3}}$$

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:

$$P_{Wout} = P_w * A * \eta_G \qquad (2)$$

Where A is the total swept area of the wind turbine in (m^2), η_G is the electrical efficiency of the wind generator and any other electrical components connected to the generator.[1]

3.2.PV Module Modeling And Simulation

3.2.1.Photovoltaic Power Modeling

Mostly there are two methods used to calculate the power produced by PV array. In (Ortiz 2006) a photovoltaic module model based on the electrical characteristics provided by the manufacturer is presented. The model predicts power production by the photovoltaic module for different temperatures and irradiance levels.[2], [3]

$$I(V) = \frac{I_x}{1 - \exp\left(\frac{-1}{b}\right)} \times \left[1 - \exp\left(\frac{V}{b \times V_x} - \frac{1}{b}\right)\right] \qquad (3)$$

$$V_x = s \times \frac{E_i}{E_{in}} \times TCV \times (T - T_N) + s \times V_{\max} - s \times (V_{\max} - V_{\min}) \times \exp\left(\frac{E_i}{E_{in}} \times \ln\left(\frac{V_{\max} - V_{oc}}{V_{\max} - V_{\min}}\right)\right) \qquad (4)$$

$$I_x = p \times \frac{E_i}{E_{in}}\left[Isc + TCI \times (T - T_N)\right] \qquad (5)$$

$$P(V) = \frac{V.I_x}{1 - \exp\left(\frac{-1}{b}\right)} \times \left[1 - \exp\left(\frac{V}{b * V_x} - \frac{1}{b}\right)\right] \qquad (6)$$

Where:-

$$bn + 1 = \frac{Vop - Voc}{Voc \times \ln\left(1 - \frac{I_{op}}{I_{sc}} \times \left(1 - \exp\left(\frac{-1}{b_n}\right)\right)\right)} \qquad (7)$$

3.2.2.Temperature and Solar Radiation Effects

The two most important effects that must be considered are due to the variable temperature and solar radiation. The effect of these two parameters must be taken into account while sizing the PV system.

3.2.2.1.Temperature Effect

This has an important effect on the power output from the cell. The temperature effect appears on the output voltage of the cell, where the voltage decreases as temperature increases. This decrease for silicon cell is approximately 2.3 mV per 1°C increase in the solar cell temperature.

The solar cell temperature T_c can be found by the following equation 8.

$$T_c = T_a + \left(\frac{NOCT - 20}{800} \right) * E_i \qquad (8)$$

3.2.2.2.Solar Radiation Effect

The solar cell characteristics are affected by the variation of illumination. Increasing the solar radiation increases in the same proportion the short circuit current. The following equation illustrates the effect of variation of radiation on the short circuit current:

$$Isc\,(E_i) = Isc\,(at 1000\,W\ /\ m^2) * (E_i\,(inW\ /\ m^2)\,/\,1000\,) \qquad (9)$$

The output power from the PV cell is affected by the variation of cell temperature and variation of incident solar radiation. The maximum power output from the PV cell can be calculated using the following equation. [2]

$$P_{out-pv} = P_{r-pv} * (E_i / E_{in}) * [1 + K_T\,(T_c - T_o)] \qquad (10)$$

(K_T = - 3.7 *10^{-3} / 1°C for mono and poly crystalline Si)

The following equation can be used to calculate the cell temperature approximately if the NOCT is not given by the manufacturer.[4]

$$T_c = T_a + 0.025 * E_i \qquad (11)$$

4.Thermal System Analysis Of Flat-Plate Collectors

The thermal energy loss from the collector to the surrounding by conduction, convection, radiation considering those three heat transfer mechanism developed energy balance collector.

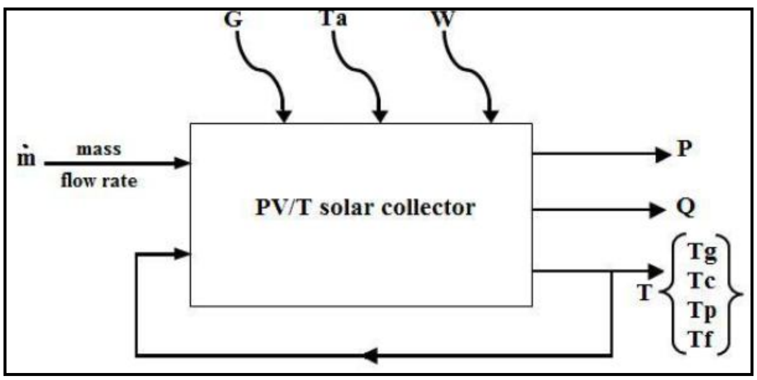

Figure 1: Energy Balance Of PVT System

5.Pump Modeling

5.1.Q-H Pump Characteristic

Water head is a term commonly used with pumps. Head represents the height of a vertical column of water. Pressure *p* and water head *H* are mutually connected concepts and in our model we use the equation:

$$H = \frac{p}{\rho g} \qquad (12)$$

Where 'ρ' is fluid density and 'g' is the gravity constant. The relationship between water flow rate and water H (pressure p) is given by the so-called Q-H characteristic for each pump.

For each pump its distinguished dynamic and static levels of the water. Dynamic pressure (dynamic level of the water), H_{dyn} is the difference between the level of water in the well and ground level, while static pressure H_{sta}; represents pressure in the main pipeline of water system.

Where:-

$$H = H_{dyn} + H_{sta} \qquad (13)$$

5.1.1.Borehole

According to Narvarte et al. (2000), the total head from borehole H_{TE}, can be expressed by the following approximate equation. [10].

$$H_{TE(i)} = H_{OT} + H_{ST(i)} + \frac{H_{DT(i)} - H_{ST(i)}}{Q_{\max}} * Q_{AP(i)} + H_{F(i)} * Q_{AP(i)} \quad (14)$$

$$Q_{AP(i)} = vQ_{d(i)} \quad (14.1)$$

i: assumes increment values *i*=1 to *N* (*N* is the total number of time stages, Months)

Apart from the aforesaid, it is important to stress the need for compatibility between discharge capacity of borehole and pumped water, i.e. that the power of the PV pumping system should be synchronized in this sense. Due to this, it is necessary to introduce constraint of water pumped daily from the borehole in period I, by the following equation.[10].

$$Q_{d(i)} = Q_{\max} t_{r(i)} \quad (15)$$

5.1.2.Water Balance Equation

Water flows into soil (reservoir) by precipitation $Re_{(i)}$, irrigation $Q_{PV(i)}$ and possibly by capillary lift from deeper layers, flows out by infiltration INF(i) and evapotranspiration ETr(i).

Soil moisture stages in i time period are denoted as $W_{(i)}$. Considering the water quantities that flow into the soil, as well as those flowing from it, and by observing soil moisture as total water quantity in soil on unit area, expressed in "mm" (1mm=10 m^3/ha), disregarding horizontal flow, at the beginning of time period *i*, the water balance equation (soil stages) for soil as water storage can be expressed as follows.[10].

$$W_{(i)} = W_{(i-1)} + (10Q_{pv(i)} / A) + \mathrm{Re}_{(i)} - ET_{r(i)} - INF_{(i)} \quad (16)$$

6. Electric Power Of The Wind And PV Generator

6.1.Nominal Electric Power of Wind Generator

The hydraulic energy required to pump at the output of a pumping system in *i* time period, which, expressed in kWh, is as follows [7]:

$$E_{H(i)} = \frac{2.72\, Q_{d(i)} H_{TE(i)}}{1000} \quad (17)$$

Including the efficiency of wind generator, water pump-motor (η_{MP}), irrigation efficiency (η_N), (it shows to what extent the water that enters a certain irrigation system is exploited). Then substituting $H_{TE(i)}$ from equation .14 the electric power consumption in kW is calculated as follows:

$$P_{electric} = \frac{2.72}{1000 \times \eta_{MP} \eta_N} \times \left\{ \begin{array}{l} (H_{OT} + H_{ST(i)} + \dfrac{H_{DT(i)} - H_{ST(i)}}{Q_{\max}} \times Q_{d(i)} + \\ H_{F(i)} \times vQ_{d(i)}) \times Q_{d(i)} \end{array} \right\} \times Q_{d(i)} \quad (18)$$

6.2.Nominal Electric Power of PV Generator

In the systematic approach to the problem of determining optimal nominal electric power of the PV generator, in this thesis is to show the direct dependency of water pumped, characteristics of the borehole, as well as irrigation method.

Therefore, the nominal electric power of PV generator is calculated based on the known monthly average daily demand for hydraulic energy E_H and available monthly average daily solar irradiation E_s in the critical month and the known efficiency of the motor–pump unit η_{MP} in referential operating conditions, taking into account the effect of outside temperature on the efficiency of the PV generator. The nominal electric power of PV generator P_{el} is expressed in (W) in referential condition is by:

$$P_{el} = \frac{1000}{f_m [1 - \alpha_c (T_c - T_o)] \eta_{MP}} \frac{E_H}{E_S} \quad (19)$$

Eq. (19) stands for critical month, i.e. the month in which the ratio between hydraulic and radiated solar energy E_H/E_S is maximum. However, this approach has some imperfection. This are Lack of systematic quality and Static quality.

But for the modern PV pumping system the load matching factor to characteristics of the PV generator is substituted by inverter and the irrigation efficiency. But for this thesis inverter is not included due increase in investment costs and efficiency of the system mainly. So the final relation for calculating electric power of the PV pumping system is obtained:

$$P_{el(i)} = \frac{2.72}{[1 - \alpha_c (T_{cell(i)} - T_o)] \eta_{MP} \eta_N E_{S(i)}} \times \left\{ \begin{array}{l} H_{OT} + H_{ST(i)} \dfrac{H_{DT(i)} - H_{ST(i)}}{Q_{\max}} vQ_{d(i)} + \\ HF\ (vQ_{d(i)}) \end{array} \right\} \times Q_{d(i)} \quad (20)$$

7.Simulation Results

The small wind turbine (whisper 200) is simulated for Debre Berhan climate condition. This wind turbine produces power at minimum wind speed (3.1 m/s), so it's suitable for Debre Berhan site for medium wind speed to give peak power to feed demand load. The whisper 200 could able irrigate 1 hectare, most of the demand is fully provided except a few months.

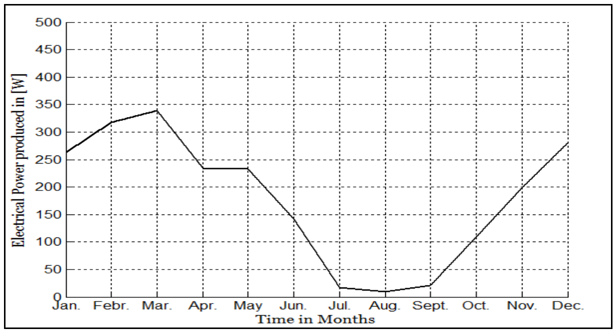

Figure 2: Electrical Power Generated Using Whisper 200

As seen in fig. 2 above, the wind power is vary in each month which indicates how wind potential is available for a site. The maximum power is harvested during the month of January-May and October-December. These months are the most critical month which high demand of power for irrigation.[5,6,7]

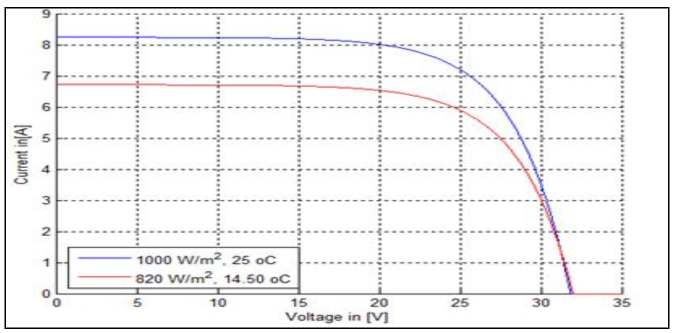

Figure 3: I-V Module Characteristics At STC And At Debre Berhan Climate

In fig. 3, the I-V curve that at 1000W/m² the module generated the same current that the manufacture specifies 8.35A. Then changing the radiation levels to 820W/m², the current of the photovoltaic module is drop to 6.75A. We can see in the I-V curve that the current drops 19.2% when the radiation level is change to 820W/m². This drops in the range of recommended losses (0%-20%) to install or use PV module for Debre Berhan site.

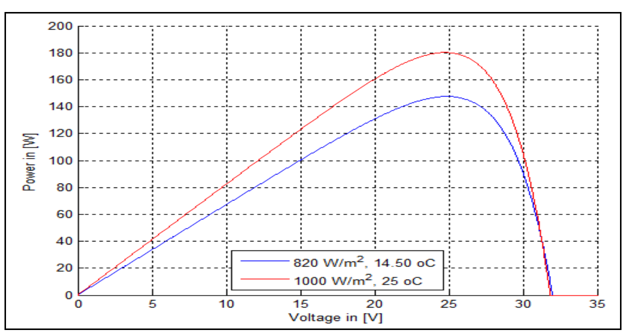

Figure 4: PV Module Power Output At STC And At Debre Berhan

The P-V curve in fig.4, at 1000W/m² the module generates the same power that the manufacture specifies 180W. When the radiation level is decreases to 820W/m² the power of photovoltaic module drops to 144.28W. This is about 19.2% when the radiation level is changed.

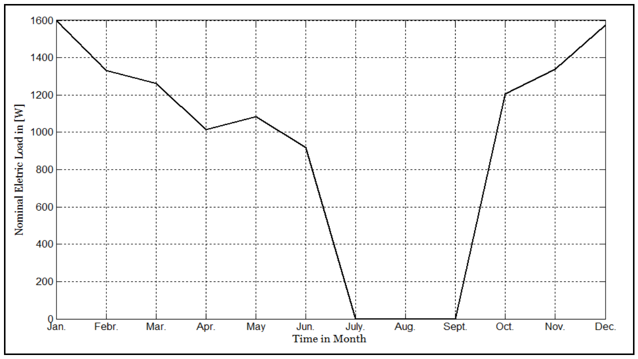

Figure 5: Electrical Power Load

Fig. 5 shows the power load (demand) needed for water pump are depends on all climate condition. These are solar insolation; temperature, soil moisture, total water level and also the hydraulic energy calculated for water pumping is not correlated to these elements, which I highly affect amount water needed by the crop and demand power.

8.Proposed Stand Alone Optimization Criteria

Now it's to formulate the stand alone hybrid sizing and optimization procedure; the linear optimization with constraints is used. The main objective of the work is to minimize the cost of equipment with optimum power supply. This can be formulated as follows:

$$EquipmentCost(C) = \sum_i C_{PVi} N_{PVi} + \sum_j C_{WTj} N_{WTj} + \sum_l C_{Cl} N_{Cl} + \sum_m C_{Pm} N_{pm} \quad (21)$$

With constraints

$$\frac{YearlyLoad}{\eta_{SA}} \leq \sum_i E_{PVi} N_{PVi} + \sum_j E_{WTj} N_{WTj} \quad (21.1)$$

$$MaximumPowerWattage \leq \sum_l P_{Cl} N_{Cl} \quad (21.2)$$

Where:-

- N_{PVi} Number of photovoltaic modules
- N_{WTj} Number of wind turbines
- N_{Cl} Number of controllers
- C_{PVi} Cost of a photovoltaic module, U.S ($)
- C_{WTj} Cost of wind turbine, in U.S ($)
- C_{Cl} Cost of controllers, in U.S ($)
- E_{PVi} kWh/year generated by photovoltaic
- E_{WTj} kWh/year generated by wind turbine j
- P_{Cl} Maximum output power of controller k
- η_{SA} Total stand alone system efficiency

The stand alone hybrid system optimization problems formulated above are compose of linear objective functions, subject to linear inequality constraints where the solution to the problem must be integer values of the variables. [8,9,10]

9.Results And Discussion

Underlying all wind turbine and photovoltaic modeling and simulation, as well as electrical output models, the meteorological data used as inputs. These include wind speed, sunshine hour daily average, average temperatures, daily precipitation, and water static head level. The wind speed and solar radiation are the crucial variables when designing and selecting wind turbine and photovoltaic respectively. Since it is directly input to wind turbine and produce the electric power, resulted value affects the amount of water pumped. Therefore, for each local, it is important to establish an accurate wind speed and solar radiation prediction in order to determine both the amount of water required and the amount of wind turbine and PV power available to deliver the demand water.

Months	Wind speed at (25m)	Solar radiation (W/m^2)	Precipitation (m^3)	Evapotranspiration (m^3)
Jan.	4.91	823.84	3.6	32.47
Feb.	6.15	877.64	5.84	35.98
Mar.	5.24	945.54	8.3	39.88
Apr.	4.77	898.18	7.6	38.54
May	4.76	890.91	8.26	41.05
Jun.	4.26	785.67	7.52	32.50
Jul.	3.29	633.84	54.4	24.14
Aug.	3.21	752.48	56.2	30.11
Sept.	3.32	766.96	49.6	31.99
Oct.	4.05	823.84	14.4	41.11
Nov.	4.59	877.64	0.6	43.13
Dec.	4.99	945.54	0.2	36.76

Table 1: Summary Of Input Data For Simulation

The available energy of the site and the required load by the irrigation is considered integrally to propose optimum hybrid. The power load (demand) needed for water pump is depends on all climate condition. These are solar insolation; temperature, soil moisture, total water level and also the hydraulic energy calculated for water pumping is not correlated to these elements, which is highly affect amount water needed by the crop and demand power. The effects of all considered elements are clearly shown in table 2. The wind and solar energy harvested from wind turbine and PV modules is shown below in figure (4). Due to the variations of renewable energy sources the power produced in each day/month is also vary. The work search for optimum solution where there is no over/under demand to decrease the energy wastage and cost increase due to this energy production. Since the climate determines the moisture/water input and wind speed, solar irradiation, for one part, and water requirements for irrigation, for the other part. Thus for maximum energy available during the month from February-April there is around 11% is excess. This because of maximum energy from both wind and solar power is generated. For the rest of month except July and August which is there is rainfall, the excess energy produced about 6%. The optimized hybrid system produces 2831.7kWh/year, 2211.86kWh/year are used by the pump. In addition to demand power load there is no unmet load and shortage of electrical power for the pump, as well as water requirement by the crop.

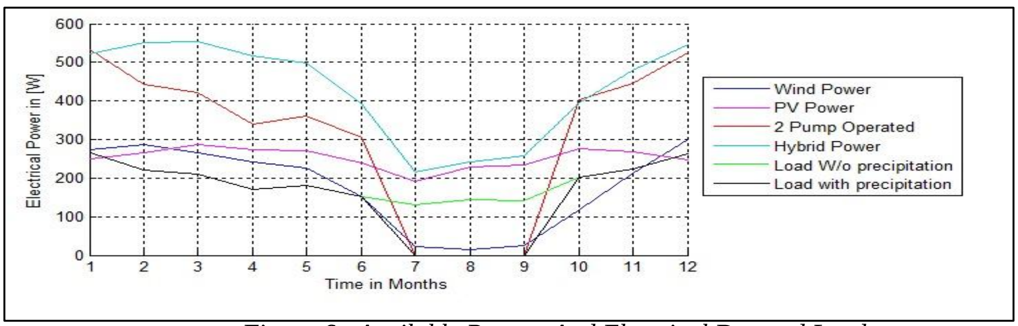

Figure 6: Available Powers And Electrical Demand Load

Months	$W_{(i-1)}$ (m^3)	$Q_{d(i)}$ (m^3/day)	$Re_{(i)}$ (m^3)	$ET_{r(i)}$ (m^3)	$W_{(i)}$ (m^3)	$P_{el(i)}$ (W)
Jan.	450.00	4.86	3.6	32.46	469.73	1597.7
Feb.	469.73	4.53	5.84	35.97	465.22	1331.2
Mar.	465.22	4.69	7.84	39.87	465.40	1263.4
Apr.	465.40	3.83	7.6	38.54	457.39	1015.5
May	457.39	4.21	8.26	41.04	459.33	1082.4
Jun.	459.33	3.02	7.52	32.49	455.26	918.8
Jul.	455.26	2.05	54.4	24.13	500.78	788.4
Aug.	500.78	2.70	56.16	30.10	503.09	863.1
Sept.	503.09	2.80	49.6	31.99	495.68	843.4
Oct.	495.68	4.69	14.4	41.11	470.26	1206.3
Nov.	470.26	5.29	0.6	43.13	460.38	1337.9
Dec.	460.38	5.72	0.2	36.76	466.89	1576

Table 2: Summarized Results Values Of Water Pumping For Debre Berhan

The available energy (capacity and needs) from hybrid system is able to irrigate around 3 hectare at a time and 6 hectare when we produce wheat crop twice in a year. Depending on the crop produced the hybrid economic evaluations have been done. The most cost effective hybrid system is shown in the fig. 5. Since the power is needed for crop production, it's not only the cost of the hybrid system, also the power required at different time should be considered. The operation time with optimum power production without storage (battery) is more preferable, due to the high cost of battery. The wind power is operate for 24 hours, where as PV is only for 7 hours daily.
Regarding for different fraction of renewable energy, i.e. using 100% wind turbine the capital cost increase by 26%, which is not affordable. Also using for 100% PV module for power production the total capital is decreased by 2% from the hybrid system. But using only PV module is a risk due to no power available for 24 hour, which affects the critical irrigation time and need a battery which adds extra capital investment.

10.Conclusion

The performed work that using hybrid wind and PV power system for irrigation application, which integrally views the power and water demand by the crop is considered. The modeling of wind resource using Weibull probability distribution and Ortiz model used, to model PV output power based on available solar radiation data has been done. Also the economic evaluation and the feasibility of the hybrid system; are approached using a Net Present Value (NPV) and Internal Rate of Return (IRR).
Thus the paper presents systematic approach to the problem (dynamic programming), taking into account all important elements. Also it has been considered the feasibility of the hybrid system for the irrigation application depends on cost analysis. As the possibilities of meeting the hydraulic energy at the output of power from hybrid system is depend on hybrid energy in the analyzed period, thus this paper optimize their relation, which is basically defines the electric power of hybrid system.

Generally it can be concluded that:

- Whisper 200 wind turbines and Kyocera 180 (KC180GT) are most economical hybrid system to generate the required energy of 2211.86kWh/year in Debre Berhan.
- The minimum demand power required to pump the water at Debre area is about 1597.7W per day to irrigate one hectare.
- Wind and PV hybrid water pumping system alleviates crops during dry season and increase productivity during shortage of rainfall.
- Avoid idle time, increase substantial income of individual farmer as well as countries economy by using land and human resource effectively throughout the year.
- The hybrid power system for irrigation application, using 6% interest rate is a good investment in Debre Berhan area. The NPV and IRR of this project reflect an income of $13,348.2 and 9% in a period of 20 years respectively.
- Using hybrid power system is more economical as the wind does not blow all the time nor does the sun shine all the time, solar or wind power alone are poor power sources. Hybridizing wind and solar power sources together to cover the periods of time without sun or wind provides a realistic form of power generation.

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