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Optimal sizing of solar water pumping system for small scale irrigation: Case study of Dangila

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Abstract: The diesel driven water pumping systems have a great impact on irrigation in remote areas around the world. However the gradual increase of fuel prices worldwide and high maintenance cost discourages the utilization of the technology. Therefore, it is important to think of an alternative energy source for such application. The optimal sizing of this PV water pumping provides theoretical studies of photovoltaics and modelling of electric power requirement for powering pump to irrigate crops as an alternative to diesel technology. The analysis employs determining the optimum tilt angle of solar panel which can collect the maximum solar energy when irrigation water demand could be higher based on seasonal Variation. The irrigation requirement has been determined by combining climate inputs, hydrology, crop type and developing stage, soil type, moisture and irrigation method etc. at each time stage of irrigation period. The power requirement has been analysed using dynamic programming by relating hydraulic load with the solar radiation energy from the solar panel for each decadal irrigation period. The maximum power has been minimized so as to select the power which can satisfy all irrigation periods with reduced cost of PV system. Furthermore Pumps (Centrifugal surfaces) with high discharge and low heads are selected to minimize water cost for such application as surface water sources from rivers and ponds are mostly applicable for irrigation in Ethiopia.

Keywords: Photovoltaic Water Pumping, Irrigation Requirement, Optimization, Dynamic Programming

1. Introduction

Energy is a critical foundation for economic growth and social progress. As economy advances and human society requires more energy, the lack of fossil energy and its effluence effect on the environment has given rise to the ever-serious contradiction among energy providing, environmental protection and economic development. Renewable energy, with the availability of its renewability and minimum pollution will grow to be an effective and practical choice to guarantee the future development of the world.

The renewable energy sources (solar, wind, geothermal, hydropower etc.) attract more attention as an alternative energy. Among the renewable energy sources, the photovoltaic energy has been widely utilized in low power applications in the world. It is also the most promising candidate for research and development for large scale users as the fabrication of low cost PV devices becomes a reality.

A recent survey by the Chinese firm Hydro china Corporation estimated Ethiopia's solar power potential to be around 2 trillion MW hours, with the northern part of the country having the greatest potential [2].

There are many studies that have been carried out for using photovoltaic as source of energy for water pumping worldwide, but this technology is still in its infant stage in Ethiopia. On the other hand most of the studies carried out are not optimal designs. They are mostly concentrated on efficiency improvement techniques and design based on peak hydraulic energy demand without considering the variation of solar energy and water requirement with time dynamically.

The performed reviews show that the previous approach to sizing the PV pumping irrigation system, which separately views the demands for hydraulic energy and possibilities of its fulfilment by PV pumping system from the available solar energy, is basically non-systematic and static, therefore is not optimal [3]. Therefore, a systematic approach has to be considered to problem solving, taking into account all relevant elements, from PV pumping system, local climate, soil, crops types and to irrigation system.

On the other hand agriculture in Ethiopia is dominated by smallholder rain-fed systems but low and unpredictable rainfall limits productivity and food security. Consequently, investment in small-scale irrigation has been identified as a key poverty reduction strategy. In addition, given the water resources potential, promoting groundwater and surface water use for fragmented land and adoption of household level irrigation technologies is crucial. In its Growth and Transformation Plan (GTP), the government of Ethiopia discussed making use of groundwater by supporting farming households in the adoption and use of private hand-dug wells and suitable water lifting technologies (WLTs).

Since most rural areas are far from the electric service in Ethiopia, most hand dug wells, shallow wells and boreholes are fitted with hand pumps or diesel and petrol driven generators. Diesel/petrol pumps have many drawbacks such as high running and maintenance costs, unreliable supply of fuel, and poor availability of spare parts. In addition some of the drawbacks of hand pumps include: requiring excess labour from women, lacks of additional services and, disrepair of the system due to the frequent contact of the hand pump by human beings and low flow rate.

In this thesis the optimal technical analysis and the economic feasibility of using PV system design for water pumping in Ethiopia particularly in Dangila for small scale irrigation application has been studied.

2. Analysis of Photovoltaic (PV) Energy for the Selected Site

The solar radiation is very important in calculating the amount of electricity generated by PV modules. The long term statistical data of solar sunshine hour is also very important in deriving an equation to calculate the solar radiation, and use in the design of the PV energy generation system. However, the solar radiation could be generated by the mathematical model which is developed based on the meteorological sunshine hour data.

The analysis follows from extra-terrestrial solar radiation calculation, monthly average terrestrial solar radiation determination up to daily solar radiation on the plane of solar module for the site.

The algorithm used to calculate the radiation on the plane of the PV array would be:

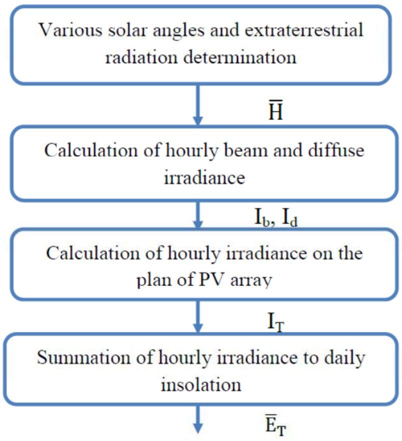

Figure 1. *Flow showing the determination of solar energy on the plane of PV panel*

3. Configuration of DC Solar Water Pumping System and Irrigation Requirement

3.1. PV Panel Tilt Angle Determination and Insolation on a Tilted Surface

The magnitude of solar radiation received by a collector is a function of many factors such as latitude, the declination angle (the angular position of the sun at solar noon with respect to the plane of the equator), tilt angle, the sunrise hour angle and the azimuth angle [8]. The inclination β to the horizontal plane of the photovoltaic panels (PV) must be to maximize the relationship between solar radiation and hydropower necessary and its relation with other angle is shown in the (fig.2). Many investigations have been carried out to determine the optimum tilt angle for solar PV modules.

The hourly insolation on a tilted surface is obtained by:

$$\bar{I}_T = \bar{I}_b \bar{R}_b + \bar{I}_d \left(\frac{1+\cos\beta}{2}\right) + \bar{I}_t \rho_g \left(\frac{1-\cos\beta}{2}\right) \qquad (1)$$

Where, $\bar{I}_T$ = hourly mean total radiation on tilted surface, Wh/m^2.

β = the PV array tilted angle

ρ_g =the ground albedo (0.2 for non-snow cover)

$\bar{I}_b$ = hourly mean beam radiation on horizontal surface, Wh/m^2.

$\bar{I}_d$ = hourly mean diffuse radiation on horizontal surface, Wh/m^2.

$\bar{I}_t$ = the hourly mean total radiation on horizontal surface,

The optimum tilt angles for solar system for periodic tracking of the sun in the region within latitudes 1° and 14° were predicted as latitude + 25° for November, December and January; latitude + 15° for February [5].

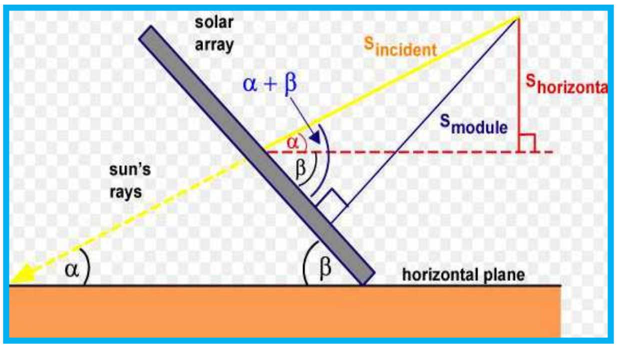

Figure 2. *Tilt angle for Solar Panel*

3.2. PV Water Pumping System Configuration

In the proposed photovoltaic water pumping system, the solar panels are directly connected to a DC motor that drives the water pump. For such simplified systems, DC motors and centrifugal pumps are required, because of their ability to be matched to the output of the solar panels.

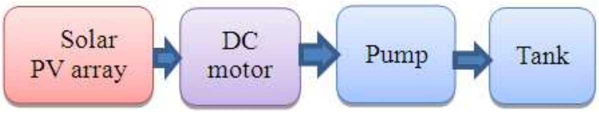

Figure 3. *Block Diagram of DC Solar Water Pumping System*

The PV pumping system would be applied conveniently to the surface irrigation/open channels/ method and drip irrigation methods, due to power requirement and way of irrigating the crop. On the other hand surface irrigation method has been commonly functional in Ethiopia. Therefore, in this research Solar PV pumping system has been analyzed using this method of irrigation.

3.3. Irrigation and Nominal Electric Power Requirement

In this study the problem is solved at each stage of the system as a technological entirety. This entirety equally encloses all components of the system, including natural processes in the system (climate, hydrology, pumping system, irrigation method etc.) during the entire period when the system is in irrigation season.

The climate determines the moisture and solar irradiation. The moisture and solar irradiation determine water requirements for irrigation. Land and geological features determine water storage capacity

Climate inputs are of stochastic character they cannot be determined explicitly. Therefore it need to be treated adequately throughout the entire operation period and the system is dynamically analyzed as veracity, taking into account all changes that occur in relation to available capacity and needs. The main components that determine hydraulic energy requirement are climate, hydrology, crop type and stage, soil type and irrigation method.

3.3.1. Soil Type and Soil Moisture

If moisture from natural processes is inadequate, irrigation is demanded. As it is known Soil moisture is a result of natural processes (precipitation, infiltration, and evapotranspiration) and characteristics of the soil.

The capacity of such water reservoir is determined by maximum water quantity that the soil can hold, i.e. by field capacity (FC). The optimal crop yield is achieved at any period i, according to Tomic (1988), when the soil moisture limit W (i), is fixed within the range of values , the wilting point of the plant and the field capacity of the soil [9]:

$$0.6\mathrm{FC} \leq \mathrm{W}_{(\mathrm{i})} \leq \mathrm{FC} \tag{2}$$

Where FC is field capacity and 0.6FC is the wilting point of the plant.

3.3.2. Water Balance

Bearing in mind the water quantities that flow into the soil, as well as those flowing from it, and by perceiving soil moisture as total water quantity in soil on a unit irrigation area, expressed in millimeters, ignoring the horizontal flow, the water balance equation at any time stage for the soil as water storage, can be expressed as follows [1]:

$$\mathrm{W}_{(\mathrm{i})} = \mathrm{W}_{(\mathrm{i}-1)} + \frac{\mathrm{Q}_{\mathrm{pv}(\mathrm{i})}}{10\mathrm{A}} + \mathrm{R}_{\mathrm{e}(\mathrm{i})} - \mathrm{INF}_{(\mathrm{i})} - \mathrm{ET}_{\mathrm{r}(\mathrm{i})} \tag{3}$$

Where, increment i assumes the values i = 1 to N (N is the total number of time stages, decades);

$W_{(i-1)}$ the soil moisture in i-1 period (mm);

$Q_{PV(i)}$ the water from PV pumping system that is, added to soil by irrigation in i period (m3);

Re $_{(i)}$ the total effective precipitation in time stage i (mm);

$ET_{r(i)}$ is quantity of water lost by the real evaporation and transpiration in i period (mm);

A irrigated area (ha); and

$INF_{(i)}$ infiltration represents the connection between the observed superficial soil layer and deeper soil layers in time stage i (mm).

By replacing solar irradiation on a horizontal surface expressed in kW h/m^2 and the ambient temperature (^{0}C), the following equation is obtained from the original form of Turc's formula for decadal evapotranspiration calculation [7];

$$\mathrm{ET}_{\mathrm{r}(\mathrm{i})} = 0.13(86.4\mathrm{E}_{\mathrm{h}(\mathrm{i})} + 50)\frac{\mathrm{T}_{\mathrm{a}(\mathrm{i})}}{\mathrm{T}_{\mathrm{a}(\mathrm{i})}+15} \tag{4}$$

where $E_{h(i)}$ the decadal average daily value of global solar irradiation on a horizontal surface (kW h/m^{2}day) and T a(i) is the decade mean daily value of air temperature (^{0}C).

3.3.3. Economical Irrigation Requirement Limit for the Pumping System

Now a day's most convenient water pump for irrigation purpose applicable in Ethiopia is diesel powered pumps. Economic estimates of various alternatives generally reduced to comparison of PV pumping system with these most effective traditional driving systems [6]. In that sense we can limit the maximum irrigation requirement that could be used economically by PV solar water pumping system, when the volume head product for daily demand of water satisfies:

$$Q_{d(i)}.H_{TE(i)} \leq 800m^4/day \tag{5}$$

Where, $H_{TE(i)}$ is the total dynamic head (m)

3.3.4. Nominal Electric Power Requirement of the PV Generator

The equation for nominal electric power of PV generator (Pel) expressed in (W), in referential condition (Standard Test Condition STC, according to Kenna and Gillett (1985) is as follows:

$$P_{el} = \frac{1000}{[1-\alpha_c(T_{c(i)}-T_o)]\eta_{mp}fm} \times \frac{E_H}{E_T} \tag{6}$$

Where,

η_{mp} Motor pump efficiency

$E_{T(i)}$ Intensity of average daily decadal solar irradiance on the tilted surface (KWh/m^2.day)

f_m the load matching factor to characteristics of the PV generator,

α_c The PV cell temperature coefficient ($^0C^{-1}$),

On the other hand the hydraulic energy ($E_{H(i)}$) expressed in kWh, which is dynamically vary with time at the output of a pumping system in i time period, as a function of flow rate requirement and total dynamic head can initially be expressed as follows:

$$E_{H(i)} = 0.00272Q_{d(i)}H_{TE(i)} \tag{7}$$

This shows that the hydraulic head requirement is basically varying with head and irrigation demand. Substituting the hydraulic equation in nominal electric power of PV generator and for DC motor pumps no need to use invertor as well as matching element. Therefore we can use motor pump efficiency η_{mp}, irrigation efficiency η_N and for set output water quantities $Q_{d(i)}$ as well as by re arranging the nominal electric power of PV pumping system is obtained here:

$$P_{el(i)} = \frac{2.72}{[1-\alpha_c(T_{c(i)}-T_o)]\eta_{mp}\eta_N} \times \frac{H_{TE(i)}}{E_{T(i)}} \times Q_{d(i)} \tag{8}$$

η_N Irrigation efficiency for set

It shows that the nominal electric power is actually a dynamic complex, non-linear function of daily pumped water $Q_{d(i)}$.

Where $T_{c(i)}$ could be determined as follows:

$$T_{C(i)} = T_{a(i)} + (\frac{NOCT-20}{0.8\bar{n}})E_{T(i)} \tag{9}$$

Where T_a is air temperature (^0C), $E_{T(i)}$ the intensity of solar irradiance on the tilted surface (KWh/m^2.day), $\bar{n}$ is monthly average daily hours of bright sunshine and NOCT is the Nominal Operating Cell Temperature (^0C). All the variables including air temperature, solar radiation, monthly average daily hours of bright sunshine, irrigation demand etc. are varying with time so does the nominal electric power.

4. Dynamic Optimal Model

4.1. Model Formulation for Optimization

Since problem is multistage, dynamic programming is used for optimal design strategy, which is the preferred technique for this kind of sequential decision problem. The required water quantity for irrigation $Q_{PV}(i)$ in a given period i (which may be month, decade, week, etc. in our case is that of decade) could also be expressed as daily value, i.e.

$$Q_{PV(i)} = n_d.Q_{d(i)} \tag{10}$$

Where n_d is the number of days in time stage i

By rearranging, the final form of water balance equation for transforming of the optimizing process is obtained:

$$W_{(i)} = W_{(i-1)} + \frac{n_d Q_{d(i)}}{10A} + R_{e(i)} - ET_{r(i)} \tag{11}$$

4.2. Defining Objectives and Constraints

4.2.1. Objectives

The objective function has been defined in optimizing relation between the output (hydraulic) energy and input (solar) energy on the PV generator $E_{H(i)}/E_{T(i)}$ at each time stage.

As investment in the PV pumping system represents costs from the buyers' point of view, it is reasonable to set the objective of achieving their minimum. In contrast, as only minimization of electric power could not be reliable for each stages, this paper has set the objective function to be minimization of the maximum nominal electric power of PV generator.

For optimization model based on dynamic programming [4], the objective function, which expresses the nominal electric power of PV generator, can be written as follows:

$$Min[maxf(W_{(i)}, Q_{d(i)})] \tag{12}$$

Optimization of nominal electric power of PV generator using dynamic recursive formula, where state variables ($W_{(i)}$) and decision variables($Q_{d(i)}$) are stated in each stage, can be written as follows:

$$f_{(i)}W_{(i)} = Min\left\{\underbrace{Max}_{Q(i)}\left[P_{el(i)}Q_{d(i)}, f_{(i-1)}W_{(i-1)}\right]\right\} \tag{13}$$

4.2.2. Constraints in the Optimization Model

Based on economic analysis for cost effectiveness of the PV pumping system in comparison to diesel pump, the decision variable has been constrained as (Eq. 5). The constraint of economically pumped water per day from a shallow well, river or pond by PV pumping system can be established by considering a maximum total dynamic head of 9 meters (5m suction head, 3.2 delivery head and 0.8m other possible head loss) for the site as:

$$0 \leq Q_{d(i)} \leq 89m^3 \tag{14}$$

Considering the fact that when precipitation exceeds evapotranspiration ($R_{e(i)} \geq ET_{r(i)}$), the model will not take into account these conditions because no need for irrigation, but only conditions when the following constraint is fulfilled:

$$ET_{r(i)} - R_{e(i)} \geq 0 \tag{15}$$

Based on local estimator programme, the periods for the analysis of the PV water pumping system is limited with range of times in which actual evapotranspiration exceeds precipitation as shown in the (fig.4)

That means irrigation is only required in seasons when actual evapotranspiration exceeds effective precipitation (from November to May) and neglecting infiltration for dry season. Otherwise, no need to pump water for irrigation. Therefore, irrigation period is chosen from the first decade of November until the third decade of May (November_1-May_3) as shown in (fig.5)

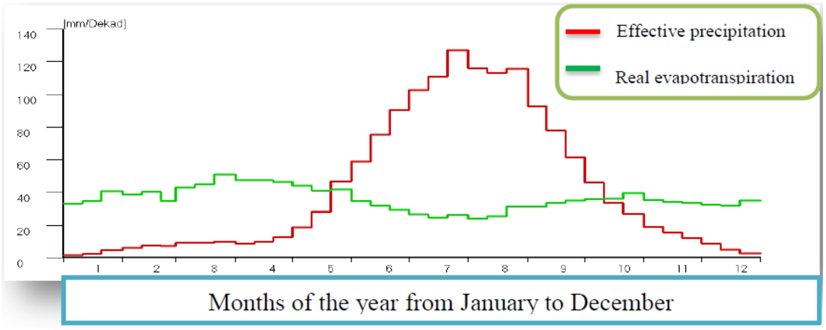

Figure 4. The relation between effective precipitation and evapotranspiration in Dangila

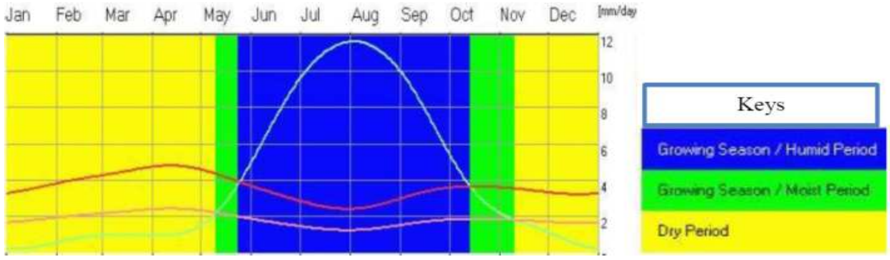

Figure 5. Months which show irrigation and non-irrigation period in Dangila

4.3. Dynamic Formulas for Optimization

Generally, by first calculating and determining in advance $E_{Tr(i)}$ from (Eq. 4), $H_{TE(i)}$ can be taken as 9 meters, α_c can be taken from module specification, FC is known from the soil type and type of crop(maize and Potato), and $T_{\text{cell}(i)}$ is also calculated in advance by (Eq. 9), analysis of nominal electric power Pel(i) by (Eq. 8) which represents the optimal return from the PV generator is possible, by taking state transformation water balance equation, i.e. (Eq. 11), and combining with all mentioned constraints at each defined time stage i, i.e.

$$\left.\begin{array}{c}
W_{(i)} = W_{(i-1)} + \frac{n_d Q_{d(i)}}{10A} + R_{e(i)} - ET_{r(i)} \\
P_{el} = \frac{2.72}{[1-\alpha_c(T_{c(i)}-T_o)]\eta_{mp}\eta_N} \times \frac{H_{TE(i)}}{E_{T(i)}} \times Q_{d(i)} \\
0 \leq Q_{d(i)} \leq 89 \\
ET_{r(i)} - R_{e(i)} \geq 0 \\
0.6FC \leq W_{(i)} \leq FC \\
W_{(i=o)} = FC,\ i = 1,2,\dots,
\end{array}\right\} \tag{16}$$

Here the objective function is calculated and the quantity of irrigation requirement and the power demand at each time stage is determined fulfilling the constraints. Optimal electric power of the PV generator, which is obtained as an output result, should meet the demands of the consumers throughout the whole observed period.

Efficiency for surface irrigation could range from 50-60%, and we could choose the minimum that is 50% efficiency as the efficiency for our design purpose.

For Dangila the soil field capacity can be taken as 450mm of water (Source: Amhara Regional Agricultural Research Institute). At a rooting depth of 0.6m for maize, FC could be =0.6x450=270mm.

5. Financial Analysis of the System

5.1. Introduction

Economic considerations are important when comparing alternative pumping methods. Solar PV pumps are technically viable but where alternatives exists the evaluation of the alternatives must include both economic and technical considerations.

The acceptance of photovoltaic in economic applications depends upon the price of photovoltaic as well as the price and availability of alternative forms of energy. Therefore, the main alternative for water pumping system is the utilization of diesel fuel powered pumps as commonly practiced in the country.

The various economic analysis methods could be used for comparison between alternatives. The main goal of this study is to select the alternative that minimizes the total cost during the proposed life cycle of each alternative and has less cost per unit water pumped.

The life-cycle cost of both alternatives mentioned in this thesis could be calculated using the formula:

$$\mathrm{LCC} = \mathrm{CC} + \mathrm{M_{PC}} + \mathrm{E_{PC}} + \mathrm{R_{PC}} - \mathrm{S_{PC}}. \tag{17}$$

Modelling and evaluating of life cycle and unit cost for each alternative has been carried out.

The capital cost (CC) of a project includes the initial capital expense for equipment, the system design, engineering, and installation.

Maintenance (M_{PC}) is the sum of all yearly operation and maintenance (O&M) costs discounted to present. Maintenance cost through life cycle is calculated using the following equation:

$$M_{PC} = A\left[\frac{(i+1)^N - 1}{i(i+1)^N}\right] \tag{18}$$

Where, A is the annual worth

i interest rate

N life cycle time (year)

The energy cost (E_{PC}) of a system is the sum of the yearly fuel cost. Energy cost is calculated separately from operation and maintenance costs, so that differential fuel inflation rates may be used. Fuel cost through the life time is calculated using the following equation:

$$\mathrm{EPC} = \mathrm{A}\left[\left(\frac{1+\mathrm{FE}}{\mathrm{i}-\mathrm{FE}}\right) * \left[1 - \left(\frac{1+\mathrm{FE}}{1+\mathrm{i}}\right)^{\mathrm{N}}\right]\right] \tag{19}$$

Where, FE is the fuel escalation rate

Here there is no energy cost incurred in case of solar PV water pumping system. This equation belongs only to diesel engine life cycle cost of fuel.

Replacement cost (R_{PC}) is the sum of all equipment replacement cost anticipated over the life of the system. Pump and motor assembly for the PV water pumping system and all components of the diesel pumping system have to be replaced after 10 years. The total replacement cost through the life time is calculated using the following equation:

$$R_{PC} = F\left[\frac{1}{(i+1)^N}\right] \tag{20}$$

Where, F is the future worth of money

The salvage value (S_{PC}) of a system is its net worth in the final year of the life-cycle period. The salvage value through the life time is calculated using the following equation:

$$S_{PC} = F\left[\frac{1}{(i+1)^N}\right] \tag{21}$$

5.2. Modelling and Calculation of LCC for Solar PV Water Pumping System

Based on the configuration, life cycle cost analysis has been performed. Excel program is used to calculate the present worth of the PV water pumping system at each time stage and overall LCC has been evaluated. Furthermore unit cost has been computed per KWh hydraulic energy and per m^3 of water output by determining the annual equivalent worth of the system. The designed programming steps for analysis are presented as follows.

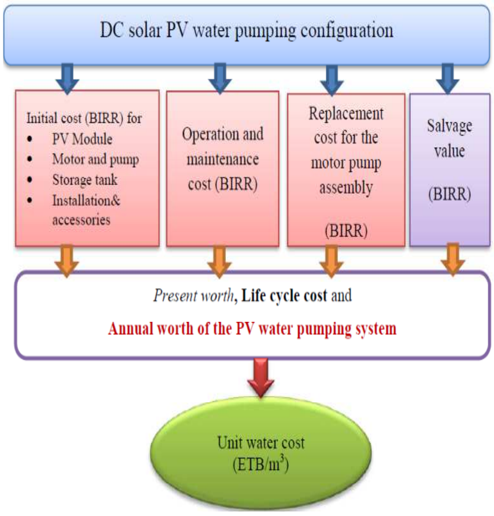

Figure 6. *LCC and unit cost calculation for DC PV water pumping system*

LCC of PV system = CC + A (P / A, i, n) +F(P / F, i , n) – F(P / F, i, n).

The unit cost of the PV water pumping system based on volume of water to be pumped has been calculated as:

Unit water cost (ETB/m^3) = Annual Cost of energy from a system / volume of water (m^3/year)

These costs have been evaluated for comparison with the diesel pumping system and to know the affordability.

The energy output can be calculated from each decadal time stages and aggregated for the effective time of the year. The annual water pumping rate is found 8840.9m^3/irrigation season.

5.3. Modelling and Calculation of LCC for Diesel Generator Water Pumping System

To validate the feasibility of PV pumping system, it must be compared with the most commonly utilized diesel powered pumping system. Therefore, here diesel engine powered water pumping system for irrigation application has been analyzed in similar manner as that of PV system. The analysis steps are also similarly presented as follows.

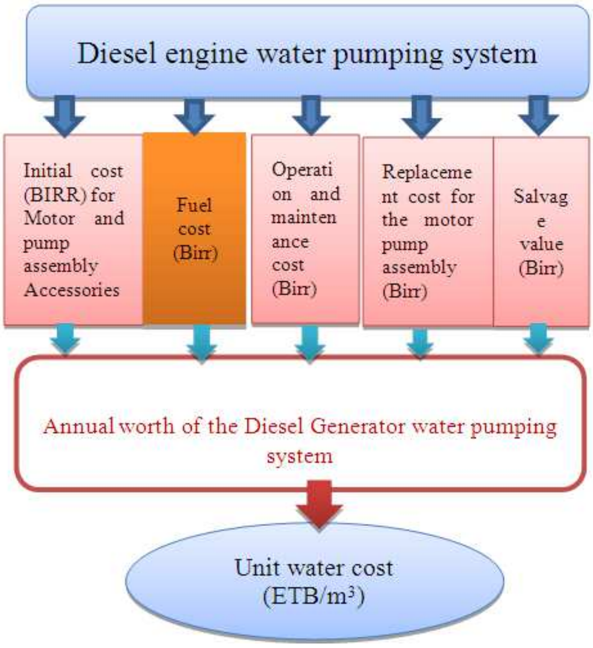

Figure 7. *LCC and unit cost calculations for diesel water*

In order to compare the two systems with the LCC comparison technique, first the two systems has been converted to equal life time that is 20 years. So, by taking one diesel generator can serve for about 10 years, after 10 years replacement of the system has been incorporated.

Salvage value is taken about 15% from diesel generator cost.

6. Results and Discussion

6.1. Solar Panel Inclination and Irrigation Requirement

Solar panels that are used for powering water pump should be set to collect the maximum amount of energy, when water demands are greatest. From the analysis we can conclude that the irrigation requirement is maximized, when the difference between actual evapotranspiration and effective precipitation is maximum. The irrigation requirement is maximized, during the months January and February. Consequently, solar panel tilt angle has to be positioned to maximize the power during these months. Therefore we could select the optimum tilt angle that optimizes the maximum load demand during January and February to be latitude + 20^0 and rounding tilt angle to as 30 degree.

This seasonal consideration of tilt angle arrangement results in 2.6-10.2% increase in efficiency of the PV panel when compared to normal yearly tilt angle arrangement for the same fixed case in the hourly insolation for the critical months(January and February).

As it is shown in (fig. 8) irrigation requirement generally increases from November to February and decreases back to the month of May. Therefore the peak irrigation water demand is found on the month of February. By the optimal nominal electric power from the PV generator the possible water flow rate is evaluated and plotted as shown in the graph. The graph shows that the peak nominal power can satisfy the overall demand during irrigation period.

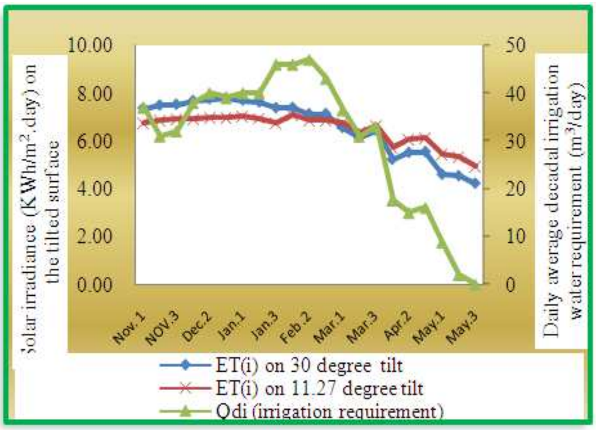

Figure 8. *Relationship between solar irradiance on PV panel and irrigation water requirement*

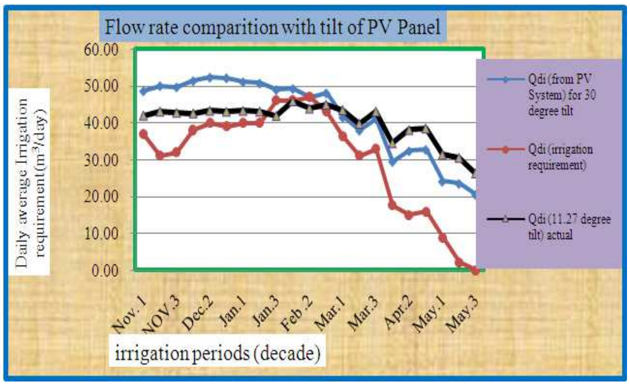

Figure 9. *Comparison between daily irrigation water demand and the possible yield of water pumped using the same designed solar power using different tilt angles*

6.2. Nominal Electric Power Requirement

The optimal electric power required from the PV generator to satisfy the hydraulic energy for irrigation has been found from dynamic optimization by iterating for each time stages. Based on daily irrigation requirement for each decade the nominal electric power has been computed. This peak nominal electric power from PV generator has been found by minimizing the maximum electric power for the irrigation period. The electric power found during the second decade of February is the peak power and has been taken as the design power for the intended purpose. Optimal electric power of the PV generator, which is obtained as an output result, could meet the demands of farmers throughout the whole observed period for irrigation area of one hectare for each period.

This optimal nominal electric power which could satisfy the demand for the whole period is 602Watt and could be taken to be 610 Watt for convenience.

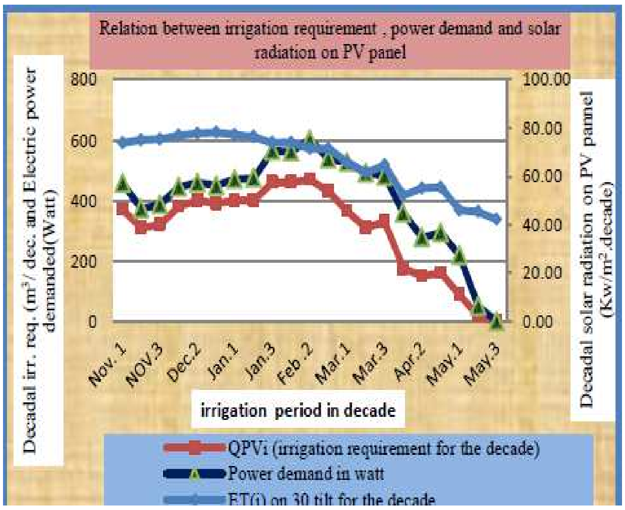

Figure 10. *Relation between solar radiation irrigation water requirement and Power demand for each time stage in irrigation period*

Table 1. *Daily irrigation requirement and electric power demand from PV generator*

Time stage(i)	$E_{T(i)}$ (KWh/m^2.day)	$Q_{d(i)}$ (m^3/day)	P_{el} (Watt)
Nov. 1	7.38	37	457.48
Nov. 2	7.51	31	372.42
NOV.3	7.54	30	362.90
Dec.1	7.69	38	444.43
Dec.2	7.77	39	447.97
Dec.3	7.81	39	449.58
Jan.1	7.71	39	459.15
Jan.2	7.64	39	462.28
Jan.3	7.39	45	552.40
Feb.1	7.40	45	549.04
Feb .2	7.14	47	601.47
Feb.3	7.15	43	537.64
Mar.1	6.57	35	506.85
Mar.2	6.16	30	475.46
Mar.3	6.46	33	482.21
Apr.1	5.22	18	366.74
Apr.2	5.52	14	259.75
Apr.3	5.54	16	293.48
May.1	4.59	8	199.18
May.2	4.53	2	51.06
May.3	4.22	0	0.00

6.3. Cost Comparison

At the first place to select cost effective solar PV water pump, pumps which has higher flow rate and low lifting heads are considered to be better choice for irrigation application. This is because the amount of water demand for irrigation is comparatively large and most of the time in our country it is possible to use ponds, rivers and low head wells for such application. Furthermore, such pumps are mostly surface pumps and their initial cost is also less costly.

The life cycle cost of PV water pumping system for 20 years is found to be 38880.43 birr and for diesel water pumping system for the same 20 years is found to be 87,063.71birr. The price of 1 m^3 of water from the PV generator costs 0.52ETB / m^3 and for that of diesel generator is 1.63 ETB/ m^3.

The breakeven point between PV water pumping system and diesel pumping system is found to be less than four years using life cycle cost comparison.

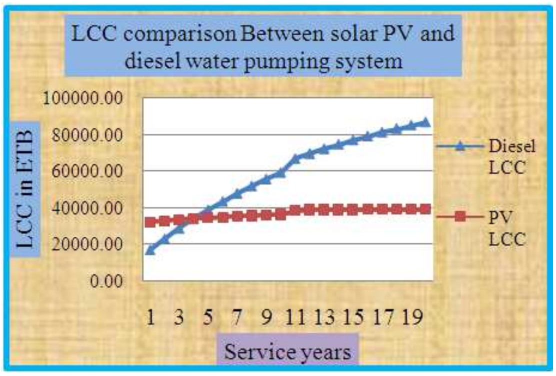

Figure 11. *LCC years to breakeven for PV vs. Diesel generator water pumping system*

7. Conclusion

Generally, the optimization of the PV pumping system for irrigation is possible when for a certain optimal policy of irrigation water distribution i.e. for corresponding values of hydraulic energy, the certain nominal power of PV generator is found, which could meet all demands in the best possible way, throughout the entire observed period.

The optimal electric power from PV generator required to supply hydraulic energy for small scale irrigation has been found using dynamic optimization to be 602 watt peak. This power could meet over all irrigation demand for all irrigation period up to one hectare irrigation area.

Solar PV power is more reliable for small scale irrigation for almost all parts of Ethiopia. This is due to the fact that solar energy is in phase with water demand to irrigate crops and there is no need for storing power in battery which could be costly. Secondly, Ethiopia has an abundant supply of solar energy throughout the year. Especially in irrigation periods i.e. from November to May the horizontal solar radiation in Dangila is more than 5.5 Kwh/m^2.day which is very promising for solar PV utilization.

Economically, the two water pumping systems (PV and diesel) has been evaluated and compared based on LCC and unit cost of water pumped. All of the cost comparisons show that solar PV water pumping system is more cost effective than diesel water pumping system.

Table 2. *Discount factor adjusted for the fuel price escalation rate and normal interest rates and LCC for each alternative*

Years	**Discount factor for costs of**				**Life cycle cost (birr) for**	
	Fuel	**Maintenance**	**Replacement**	**Salvage**	**Diesel pumping**	**PV Pumping**
1	0.955	0.909	0.909	0.909	17171.53	32036.55
2	1.866	1.736	0.826	0.826	23207.08	32683.40
3	2.735	2.487	0.751	0.751	28848.04	33271.46
4	3.566	3.170	0.683	0.683	34123.28	33806.05
5	4.358	3.791	0.621	0.621	39059.35	34292.05
6	5.115	4.355	0.564	0.564	43680.71	34733.86
7	5.837	4.868	0.513	0.513	48009.88	35135.51
8	6.526	5.335	0.467	0.467	52067.61	35500.65
9	7.184	5.759	0.424	0.424	55873.02	35832.59
10	7.812	6.145	0.386	0.386	59443.74	36134.35
11	8.411	6.495	0.350	0.350	67001.99	38511.65
12	8.983	6.814	0.319	0.319	69768.59	38569.86
13	9.530	7.103	0.290	0.290	72380.45	38622.78
14	10.051	7.367	0.263	0.263	74847.24	38670.89
15	10.549	7.606	0.239	0.239	77177.95	38714.63
16	11.024	7.824	0.218	0.218	79380.95	38754.39
17	11.477	8.022	0.198	0.198	81464.01	38790.54
18	11.910	8.201	0.180	0.180	83434.40	38823.40
19	12.323	8.365	0.164	0.164	85298.86	38853.27
20	12.718	8.514	0.149	0.149	87063.71	38880.43

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