Solar Pump Application in Rural Water Supply - A Case Study from Ethiopia

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***Abstract*- Utilization of solar energy for drinking water supply pumping is a feasible solution especially for remote villages and homes far from power grid. Using photovoltaic (PV) pumps has predominant advantages where grid connection is not available, good solar conditions exist, and distances from transport facilities are long.**

In solar powered pumps, pumping and transporting water from the source to end user requires a lot of energy. The energy required for pumping and transporting water can be obtained from solar powered pumps. The overall objective of this paper is to study the feasibility of solar powered pump/solar photovoltaic pump for drinking water supply in rural areas of Ethiopia and to compare the economics of photovoltaic pump with diesel generator powered pump.

Keywords*- *Solar Pump; Solar Energy; Drinking Water; Solar water pumping; PV Sizing

I. INTRODUCTION

Pumping drinking water from water supply sources such as borehole requires a huge amount of energy. In rural and off-grid villages of Ethiopia, diesel generator is widely used as a source of energy for pumping water from borehole or other sources of water supply in rural part of the country. As the price of fuel oil is increasing globally from time to time, using renewable energy like solar energy and wind energy as alternative sources of energy for pumping drinking water for remote rural area in countries like Ethiopia has dual advantages: 1) using the natural available resources and 2) saving the foreign exchange cost spent to import fuel oil. Developing a grid system is often too expensive because settlements of rural villages are located too far from existing grid lines, also dependence on an imported fuel supply is difficult and risky, foreign exchange rates fluctuate and the economy of many developing countries can then plummet [13].

Ethiopia has favourable solar energy resources to use for off-grid photo voltaic (PV) systems for rural population. The study also indicates that due to high prices of fuel oil, even larger photo voltaic systems are very competitive to diesel generator and village power supply [3]. PV water pumping systems may be the most cost-effective water pumping option in locations where there is no existing power line. When properly sized and installed, PV water pumps are very reliable and require little maintenance.

II. METHODOLOGY

Following methodology has been adopted for present feasibility study and comparative analysis of the solar powered pumps.

- Water supply demand analysis based on population data and national standard water provision of the country;
- To determine the energy required from the source and the size of photovoltaic module;
- Economic analysis of the system in general and cost comparison of different energy sources.

Basic steps involved in system sizing are [8]:

- Determine the water demand;
- Use design-month insolation (hours @ 1-sun) as the hours of pumping to find the pumping rate;
- Find the total dynamic head H Vs Q;
- Find a pump capable of delivering the desired head H and flow Q, Pump efficiency ηP.

III. LOCATION OF THE STUDY AREA

Ethiopia located very close to the equator between 3^0 and 15^0 N, receives abundant solar energy potential which can be harnessed and used in the form of both thermal and electrical energy. The average solar radiation is around 5.2 kWh/m^2, which is more or less uniform. The value varies seasonally from a minimum of 4.55 kWh/m^2 in July to a maximum of 5.55 kWh/m^2 in February and March. With location the radiation varies more widely between 4.25 kWh/m^2 in extreme western low lands and 6.25 kWh/m^2 in northern part of the country.

Ethiopian Rural Energy Development and Promotion Centre [7] has quantified the technical potentials of solar energy resource for different applications, as shown in Fig. 1. The solar potential GIS map was also developed. Fig 1 is showing this GIS map with study area located onto it. Geographically the study area is located at about $8^0$42' North and $40^0$54' East in Ethiopia at an elevation about 1411 meters above sea level (m.a.s.l). The area is known with its low annual rainfall distribution.

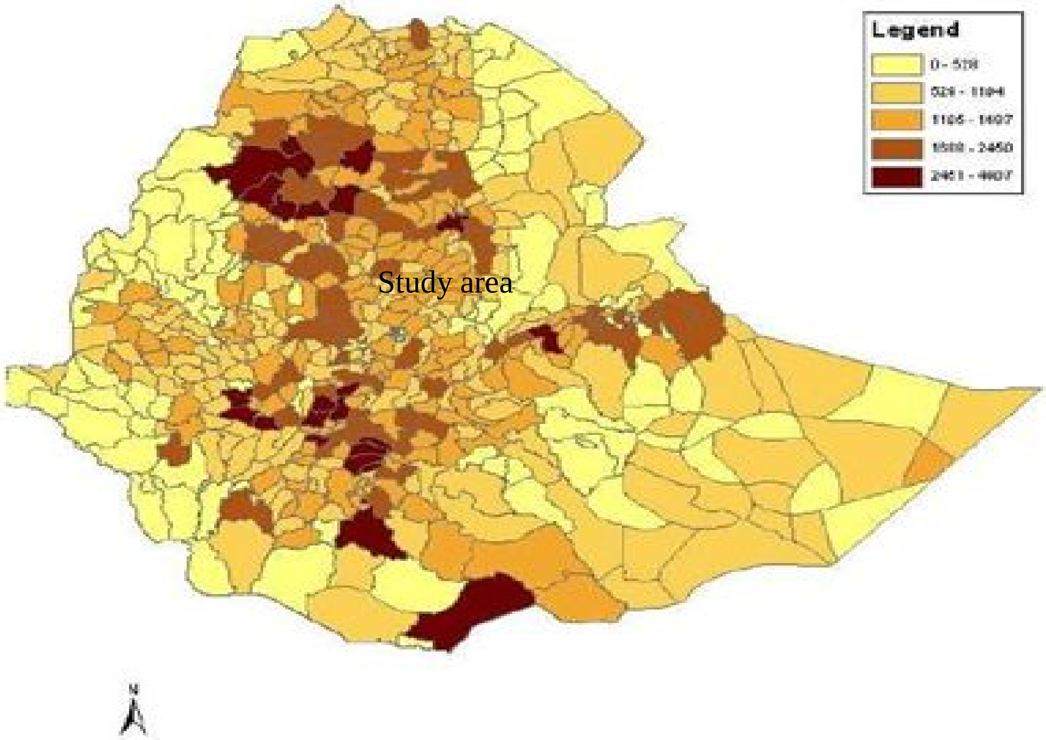

Fig. 1 Potential of PV for domestic water pumping as adopted from Ethiopian Rural Energy Development and Promotion Center.

A. Population and Water Demand

According to 2007 population census of Ethiopia the population of the study area is about 2083 persons, the population to be served at the end of design period of the scheme is about 3307 persons, as shown in Table 1.

The water demand provided in Ethiopia for rural water supply system is usually 15 litres per capita per day and the same figure is adopted for design of the system (MoWR, 2002, Ethiopia). The average daily water demand is determined by multiplying the number of user community by daily water demand per capita per day; allowances should be done for losses due to water losses in the system. The daily water requirement for the village under the study area is shown in Table 2.

TABLE 1 PRESENT AND FUTURE POPULATIONS FORECASTED FOR WATER SUPPLY SCHEME

S. No.	Entity	measure
1	Total Population (number)	2250
2	Annual growth rate (%)	2.6
3	Design year(Life of the system)	15
4	Daily water demand per capita (lit/cap)	15
5	Allowance for Losses (%)	5
	Demand Calculation**:**	
6	Year	2010
7	Population	2250

Source: Data is obtained from CSA, Ethiopia, 2007

TABLE 2 DAILY DOMESTIC WATER DEMAND

S. No.	Entity	Measure	
1	Daily water Demand (lit/capita/day)	15	
2	Allowance for losses in % of daily demand)	5	
3	Annual population growth rate (%)	2.6	
4	Year	2010	2025
5	Population	2250	3307
6	Daily water Demand (m3/day)	34	50
7	Average water Demand including losses (m3/day)	35.4	52
8	Minimum yield required from source for 6 pumping hours (l/s)	1.64	2.41

IV. SOLAR PUMPING SYSTEM

Photovoltaic pumping system (PVPS) consists of a PV array and a pumping subsystem. The principal component of the PV array is the PV solar cells which convert the solar radiation received on the surface of the PV cells into electric energy. The pumping subsystem is composed of a motor-pump set and a power conditioning equipment. Motor-pump set pumps the water in the daytime to fill a storage tank; built for the purpose [1]. Further this stored water is pumped for the drinking purpose.

A. Designing Solar Pumping System

Total dynamic head and flow rate are the two fundamental factors to be considered in water supply pump selection. Water source yield, daily water volume requirement, availability of solar insolation, pumping time, static water level discharge and pumping subsystem efficiency are the key factors required for designing a PV water pumping system. PV pump components have to be selected carefully for proper matching of the system. Unlike conventional pumping systems, PV pumps have to be designed and installed tactically to be competitive with other pumping technologies [13, 14]. A typical solar pumping system schematic is shown in Fig 2.

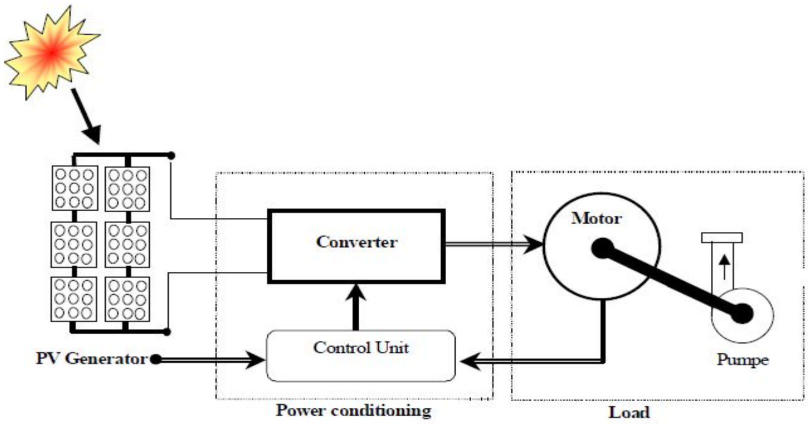

Fig. 2 Schematics of a photovoltaic pumping system adapted from photovoltaic pumping systems technologies trends (adopted from [2])

Sizing of photovoltaic pump involves determining the volume of water required to be supplied per day in m^3/day, head of water against which the pump works, and yield of water from the source of water supply. PV systems are usually sized based on the average value of energy required, availability of solar energy, and components efficiencies [6]. Storage tank sizing for drinking water considers the number of days, usually two to three days, for which water has to be stored [12].

Array sizing is a function of solar data. It represents a key factor in the viability of PV pumping systems. Erroneous estimates of insolation have resulted in underpowered or overpowered systems, causing some systems to fail to meet water demand or to be excessively and unnecessarily costly [5].

The hydraulic energy required to lift water from a lower elevation (lower water level) to a higher elevation (higher water level) can be defined by the product of mass of water, water head (H), and acceleration due to gravity g [11, 15]. Thus, Hydraulic Energy or power required to run a pump can be expressed as,

$$E_{hyd} = mgH \tag{1}$$

Where, E_{hyd} is hydraulic energy in Joule, *m* is mass in kg, *Q* is discharge or flow rate in $m^{3/}$s, g is acceleration due to gravity (9.81 m/s^2), γ is unit weight of water in kN/m^3, *H* is total dynamic head against which the pump is required to operate. Total dynamic head is the sum of total static head or lift, i.e. the elevation difference between the water source and point of delivery and total head loss (including losses through valves, bend and other fitting) through the suction and delivery pipe. The head loss in water distribution system can be calculated as:

$$H_L = \frac{1}{0.094} * \left(\frac{Q}{C}\right)^{1.85} * \frac{L}{d^{4.87}} \tag{2}$$

Where, H_L is head loss due to friction, Q is flow in pipe in m^3/s, d is pipe diameter in m, C is coefficient of roughness of pipe. Velocity of water (in m/s) is,

$$V = 0.85 * C_H * R^{0.63} * S^{0.54} \tag{3}$$

where,

$$S = \frac{H_L}{L} \tag{4}$$

R is hydraulic radius or hydraulic mean depth, S is friction slope, L is pipe length in m, Thus, total dynamic head in m can be written as,

$$H = H_{stat} + H_L \tag{5}$$

Where, H_{stat} is static head in m.

The hydraulic energy E_{hyd} from solar source in kWh/day can be given as (W. Bucher 1996),

$$E_{hyd} = Kc * \rho * g * V_o * H \tag{6}$$

Where E_{hyd} is hydraulic energy in kW/day, K_c is a conversion factor used to convert kJ to kWh, V_o is volume of water required in m^3/day, H is head of water or elevation difference between the source of water supply and reservoir outlet in *m*, ρ is density of water, usually 1000 Kg/m^3, g is acceleration due to gravity, 9.81 m/sec^2. The solar array power required (kWp) can be given as

$$E_{sol} = \frac{E_{hyd}}{I * F * E} \tag{7}$$

Where, E_{sol} is solar array power (kWp), F is array mismatch factor (0.85 on average), E is daily subsystem efficiency (typically varies from 0.25 to 0.4), I is average daily solar irradiation (in kWh/m²/day)

The number of PV modules in series can be estimated as,

$$modu \quad es \quad series = \frac{pump \quad olt}{olt \quad /modul} \tag{8}$$

The number of PV strings in parallel can be estimated as,

$$um \quad eorf \; s \quad ri \quad = s\frac{pump\,input \quad o}{no.o \quad in \quad i \; /modul * \; *d \quad tin} \tag{9}$$

Where IR is the PV rated current at STC, de-rating factor takes into account dirt and temperature effects (usually 0.80). After having sized the system, the water pumped can be estimated as,

$$m3/da \quad = \frac{olt}{modul} * \quad * \quad um \quad eorf \quad odu \quad e \quad ea \frac{}{d} * 3.6 * dera \quad i \; * \quad / \quad * \tag{10}$$

B. Designing Outcome for the Study Area

The daily water requirement for the study area is 52 m^3/day. Total pumping head (dynamic head) is 128 m. A Grundfos make pump with a capacity to pump water from a depth of 100-200 m with a nominal voltage of 120 V and power 1500 W was selected. Canadian photovoltaic module with 230 Wp, 25 V and IR of 7.78 is selected as solar PV system. Monthly average solar insolation incident on the horizontal surface in the study area is provided in the Table 3. After several calculations the required pump size, available power, solar PV array power output and other required parameters are determined. Solar array power required and number of PV panel required for PV pump subsystem for different insolation values are given in Table 4.

TABLE 3 MONTHLY AVERAGED SOLAR INSOLATION INCIDENT ON A HORIZONTAL SURFACE

Month	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
E(kWh/m^2/day	6.19	6.68	6.48	6.11	6.32	6.13	5.71	5.87	6.18	5.86	6.05	6.02

(Source NASA website data at http://eosweb.larc.nasa.gov [10])

TABLE 4 ARRAY LOAD POWER AND NUMBER OF PV REQUIRED FOR PVP SUB SYSTEM FOR DIFFERENT INSOLATION VALUES

S. No	Description	Solar Insolation ($kwh/m^2/day$)			Modules in series	Strings		
		5.71	6.13	6.68		5.71	6.13	6.68
1	Total drilled depth (m)	123	123	123				
2	Borehole depth internal diameter (mm)	150	150	150				
3	Static Water level	67	67	67				
4	pump position (depth of inlet) (m)	110	110	110				
5	safe yield (l/s)	8	8	8				
6	Design discharge	2.53	2.53	2.53				
7	Dynamic water level for design discharge	68	68	68				
8	Rising Main							
9	borehole elevation (a.m.s.l)	1379	1379	1379				
10	service reservoir elevation (a.m.s.l)	1385	1385	1385				
11	length of rising main from top of borehole to reservoir (m)	462	462	462				
12	length of rising main inside borehole (m)	110	110	110				
13	Total length of rising main	572	572	572				
14	Most economic pipe diameter for rising main (mm)	60	60	60				
15	Selected rising main diameter(mm)	62.5	62.5	62.5				
16	Velocity of water in rising main (m/s)	0.82	0.82	0.82				
17	**Pump Design**							
18	Hazen William coefficient for design life	115	115	115				
19	Static head	116	116	116				
20	friction loss in pipe	11	11	11				
21	friction allowance for fittings (assume 10 % of friction Loss in Pipe	1.1	1.1	1.1				
22	Total pumping head (design Pump head)	128	128	128				
23	Hydraulic Energy Required (kc*ρ*g*V*h, kc=1/3600	18	18	18				
24	solar Array power required (Hydraulic Energy Required /*E^{**}) (Kwh/day)	36	36	36				
25	Solar Array load to reserve water for two days (Solar power required*number of days/insolation*mismatch factor)	15	14	12				
26	**Number of PV module /panel**							
26.1	230 Wp (Canadian solar) model CS6P-230(29.6 V_{mp} , 7.76 I A_{mp})	82	76	66	5	16	15	13
26.2	235 Wp (Canadian solar) model CS6P-230	80	74	64	5	16	14	12
26.3	240 Wp(Canadian solar) CS6P-240	78	73	63	5	15	14	12
26.3	250 Wp(Canadian solar) CS6P-250	75	70	60	5	15	14	12
26.4	260 Wp (Sun tech power solar panel 260 watts $V_{mp=}$34.8 $V_{mp,}$ $I_{mp=}$7.47 I_{mp})	73	68	58	4	18	17	14
26.5	270 Wp(Sun tech power solar panel 270 watts Vmp=35 Vmp, Imp =7.71 I_{mp})	70	65	56	4	17	16	14
26.6	275 Wp(Sun tech power solar panel 275 watts Vmp=35.1 Vmp,Imp =7.84 I_{mp})	68	64	55	4	17	16	13

F^*= mismatch factor usually 0.85 E^{**}= the motor pump subsystem efficiency 35-50%, derating 0.8 for temp & dirt Grundfos pump with a Capacity to pump water from a depth of 100-200 m with a nominal voltage of 120 V and power 1500 W

V. ECONOMIC FEASIBILITY OF PROPOSED PV PUMP SUBSYSTEM

Economic comparison between PV pumps and diesel driven generator pump options is compared for 25 years of pumping time. The comparison was made by LCC method based on the assumption that both pumping systems should satisfy the volume of water required by the user community. The diesel generator pump powered with a capacity of 10 kW and the PV array load of 15 kW (using minimum solar available at the site) are compared to satisfy the same water requirement of the user community. In order to calculate all costs, the future costs are reduced to the present value using a discount rate. To compare the considered pumping options, two different scenarios are considered, the first option considers the ideal scenario of same fuel oil price for the next 25 years and the second option considers the fuel price escalation by 4% to 10% per annum. (Although the current situation is even higher than this value due to the instability of oil producing counties and as a result the fuel oil is increased in Ethiopia by 22% only in three months, which is 7.3% per month on average).

Both scenarios were applied to study the effect of change of parameter on the cost of the pumping system. Weather and market constraints were also assessed. The sensitivity analysis for weather is based on the effect of maximum and minimum solar insolation available, on the overall price of the water pumping systems. The market constraints consider what will happen if the current price of the fuel oil is increased in the coming life cycle of the systems by different percentages. In addition it tries to study the effect of purchasing the expensive photovoltaic arrays from the market. Using the maximum available solar radiation at the site in combination with lowest photovoltaic array price is considered as the best case as opposite to minimum solar radiation and more expensive PV array. The analysis for fuel oil inflation is based on the increment of fuel by different percentages (2 to 10 percent), whereas the analysis concerning PV array is based on the market price available from different PV manufacturers. Though PV module has a declining trend in price, in this analysis it is considered as constant for the coming 25 years. Figure 3 shows the economic comparison of photovoltaic and diesel powered pumping for the next 25 years whereas Figure 4 shows the sensitivity analysis of minimum solar insolation in combination with high PV module price and diesel generator pumping system.

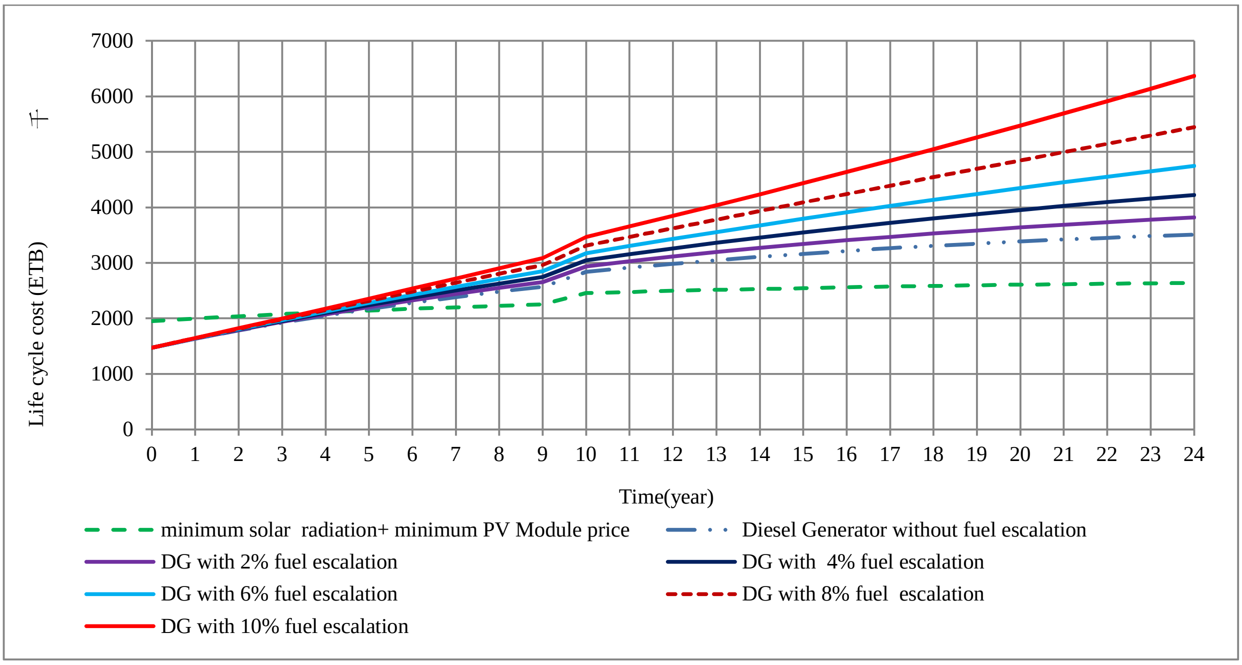

Fig. 3 Economic comparison of photovoltaic and diesel powered pumping

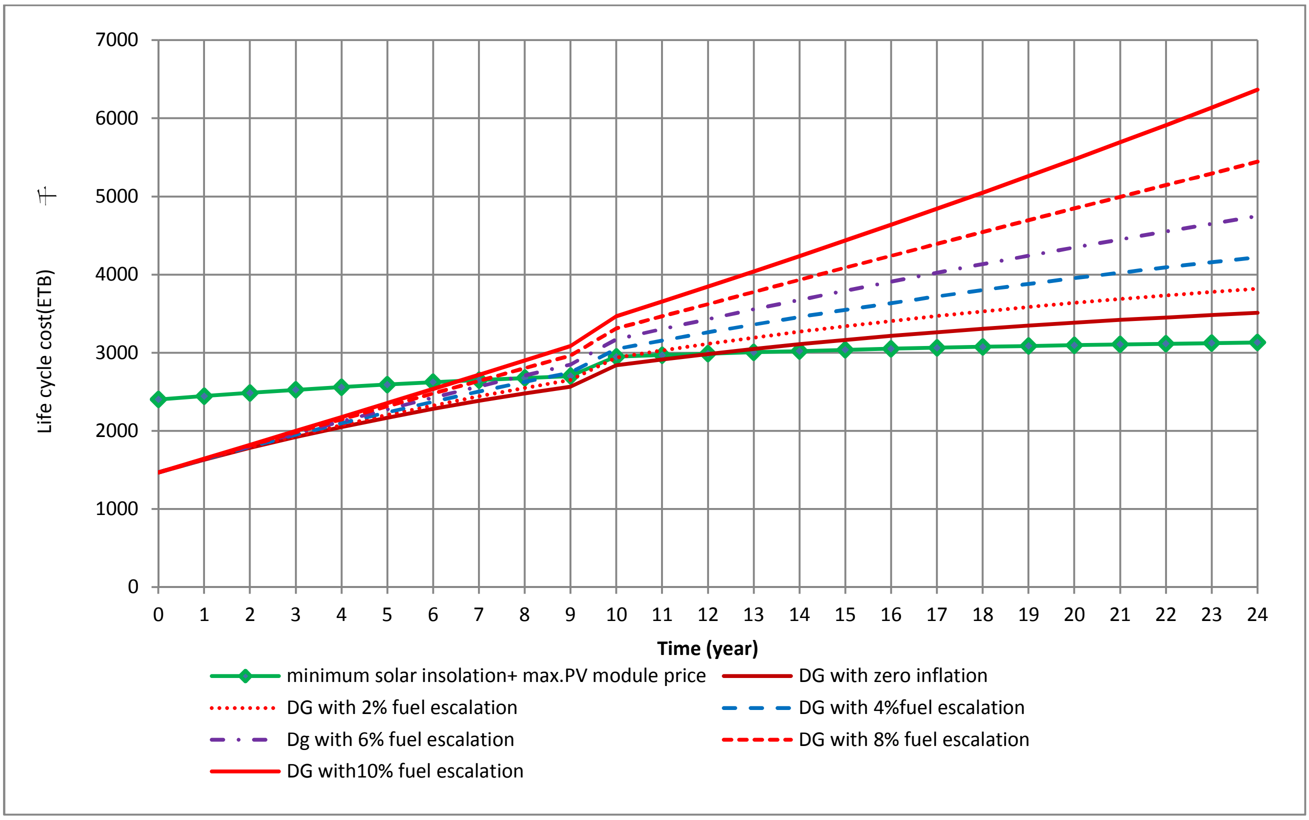

Fig. 4 Sensitivity analysis of minimum solar insolation in combination of high PV module price and diesel generator pumping system

VI. RESULT ANALYSIS

The graph in Fig. 3 shows that diesel generator powered pump is more economical than PV pumps for the first 4 to 5 years irrespective of price escalation in percentage. However, at the end of 4^{th} or 5^{th} year both solar powered pump and diesel powered pump have the same pumping cost, while for the remaining pumping period solar powered pump has an economical advantage over the diesel powered pump. Similarly, the graph shown in Figure 4 (Displays worst case of minimum solar insolation and the maximum PV array price) shows that pumping water with diesel generator is a better economical option for the first 7 to 12 years depending on fuel escalation percentage, that is, when the price of fuel is escalated at 10 % the diesel generator has an economical advantage for the first 7 years while PV powered pumps remain economical for the remaining life period. Likewise, if there is no price escalation in fuel, diesel powered pump has an economical advantage for the first 12 years and then PV pump takes over for the remaining life time of pumping time.

In general, the result shows that the life cycle cost of water pumping is sensitive to both solar insolation (weather data) and price escalation of fuel oil. The change in price of fuel oil by 4% from the current market results in an increase of 20% of the life cycle cost of the diesel generator powered pumps whereas an escalation of fuel price by 10% results in an increase of about 80% in life cycle cost of diesel generator operated pump due to high annual operation and maintenance cost. Likewise, if the pumping system is designed based on the available maximum solar insolation the life cycle cost of photovoltaic pump is reduced by 4.5%.

VII. CONCLUSIONS

Feasibility analysis of a solar PV pumping subsystem has been done in the present work to provide drinking water solution in the rural Ethiopia. Ethiopia is situated near equator and hence solar insolation potential is sufficiently available here. For a selected study area in Ethiopia, with the available solar potential, a solar PV pumping subsystem is designed for the drinking water requirement of that area. Furthermore, the economy of this pumping system is established by comparing this system with diesel pumping system. The initial cost of solar PV pumping subsystem is higher than that of diesel pumping system. Solar pumping system gets economic advantage after 4 years of working. Considering diesel price escalation, the economic advantage of solar pumping system is even higher. 2% to 8% fuel escalation situations are considered and presented here, which make our recommendations much stronger.

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