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Research article

Feasibility study of a solar photovoltaic water pumping system for rural Ethiopia

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Abstract: Solar Photovoltaic (SPV) water pumping system is one of the best technologies that utilize the solar energy to pump water from deep well underground water sources and to provide clean drinking water worldwide. The availability of abundant solar radiation and enough underground water sources in Ethiopia can be combined together to make clean drinking water available to rural communities. The software PVsyst 5.56 was used to study the feasibility of solar photovoltaic water pumping system in the selected sites. The designed system is capable of providing a daily average of 10.5, 7 and 6.5 m^3/day for 700, 467 and 433 people in Siadberand Wayu, Wolmera and Enderta sites respectively, with average daily water consumption of 15 liters per day per person and the costs of water without any subsidy, are approximately 0.1, 0.14 and 0.16 \$/$m^3$for each site respectively. If diesel generator is used instead of solar photovoltaic water pumping system, to provide the same average daily water for the selected community, the costs of water without any subsidy are approximately 0.2, 0.23 and 0.27 \$/m^3 for each site respectively. A life cycle cost analysis method was also carried out for economic comparison between solar PV and the diesel pumping system. The results of this study are encouraging the use of the PV system for drinking water supply in the remote areas of the country.

Keywords: water; solar pump; diesel; solar photovoltaic; PVsyst; economic evaluation

Nomenclature:

GOE	Government of Ethiopia
GEF	Global Environmental Facility
AWF	Africa Water Facility
UAP	Universal Access Program
MDG	Millennium Development Goal
SPV	Solar Photovoltaic
PWF	Present Worth Factor
CRF	Capital Recovery Factor
O&M	Operation and Maintenance Cost
LCC	Life Cycle Cost
MC	Maintenance Cost
PV	Photovoltaic
DP	Diesel Pump
DC	Direct Current
CC	Capital Cost
EC	Energy Cost
RC	Replacement Cost
SC	Selvage Cost
FE	Fuel Escalation Rate
d	Discount Rate
N	Life Time Period
i	Interest Rate
C_y	Annualized Capital Cost
A_y	Annualized Life Cycle Cost
C_k	Present Worth of Replacement at Year K
R_k	Cost of Replacement of a System Component at Year K
R_y	Present worth of All Replacement, Incurred during the Life Time N
M_y	Yearly Operating and Maintenance Cost of the Initial Capital Cost C

1. Introduction

The focus of this paper is on the feasibility of solar PV water pumping system for rural areas in Ethiopia. The paper is part of an ongoing research project under the supervision of Addis Ababa institute of technology. The objective of the research is to study the feasibility of solar photovoltaic water pumping system for drinking water supply to three selected rural areas in Ethiopia.

In Ethiopia, 85% of the population live in rural areas and 15% lives in urban. According to the Growth and Transformation Plan (2010), the drinking water supply coverage is 65.8% (91.5% urban and 62% rural) [1]. While there has been significant progress in recent years, there are still close to 30 million Ethiopians who lack access to safe and reliable sources of drinking water [1]. Because of this reason, in Ethiopia 46% of under-five-year's children are die related to waterborne diseases [2].

In some areas of the country the traditional water pumping systems powered by diesel or gasoline engines have been used for long time, but fuel cost, transportation problem, lack of skilled personnel makes the conventional water pumping system unreliable and expensive for rural communities.

In developing countries like Ethiopia, generally composed of several villages sparsely located and with different topography, it is very difficult to extend the electric grid to every location where it is required. Also, the lack of safe drinking water is still an issue to be solved in many developing countries, especially in rural areas [3]. The trend of increasing fossil fuel price and its high contribution to environmental problems makes fossil energy sources unpromising. Different researches have been carried out and their results show that, renewable energies are the best alternative energy sources to replace the fossil energy.

Many researchers have studied the application of solar PV water pumping systems; Asefa K. et al. [4] have studied the application of solar pump in rural areas of Ethiopia. N. Argaw et al. [5] have discussed the application of renewable energy in rural village. Kala M. et al. [6] have studied solar photovoltaic water pumping for remote location. Regarding the feasibility study A. Raturi [7] has studied the feasibility of a solar water pumping system by selecting one rural village of Fiji Island. C. Gopal et al. [8] have done a literature review of renewable energy source water pumping systems. In addition, many researchers have conducted different researches based on the design and modeling of the PVWPSs. Pietro E. et al. [9] have developed dynamic modeling tools of a PV water pumping system by combining the models of the solar PV power, the water demand and the pumping system, which can be used to verify the design procedure in terms of matching between water demand and water supply. A.A. Ghoneim [10] has developed a computer simulation program to determine the performance of the proposed photovoltaic-powered water pumping systems. C.K. Panigrahi et al. [11] have done a design and modeling of the photovoltaic water pumping system. K. G. Mansaray [12] has discussed the application of computer simulation for optimum design of the solar photovoltaic pumping system. The economic performance and comparison also carried out by Robert F. and Alma C. [13] focused on solar water pumping advances and comparative economics. According to, Robert F. and Alma C. Research PV water pumping is the most cost effective for steady pumping needs such as community water supply or livestock watering. Robert F. et al. [14] have done a life cycle cost analysis for photovoltaic water pumping system in Mexico. [15] Has discussed a cost and reliability comparison between solar and diesel powered pumps.

The main research and development (R&D) barriers for the implementation of solar photovoltaic water pumping systems in developing countries is not only the technology. There are limitations, including water resource availability, solar energy potential, water demand, acceptance and management of the system. The possibilities for development of this solution in a given site are related to the specific resources of the site and every study should start with a site resource assessment.

Now a day, the PV module costs are reduced all over the world. However, the capital cost of a solar photovoltaic water pumping system is still higher than the conventional diesel engines water pumping system. The capital cost of PV water pumping system can be considered as the major barrier for the application of the system in a developing country like Ethiopia. Therefore, optimization efforts are mainly focused on minimizing the capital cost of the system.

In this paper, PVsyst software is used for design, simulation and economic analysis of solar photovoltaic water pumping system. The solar data, well characteristics, water demand and storage tank size are input to PVsyst. In addition, the cost and lifetime of PV module, solar pump and controller are input to the software. The output of the software includes the amount of water delivered to the users, the amount of missing water, the excess (unused) PV energy and the system efficiency (performance ratio) during the year. Furthermore, the economic analysis of the software helps to determine the global investment, yearly cost and cost of water in cubic meters. The life cycle cost analysis also carried out in this paper for the comparison between solar photovoltaic and conventional diesel water pumping system. The results of this comparison show that more SPV systems can be installed in the country, replacing the existing more expensive Diesel systems, which would play a significant role in achieving the country's MDG targets.

Some statistical data for Ethiopia are shown in Table 1 and the nine administration regions are shown in Figure 1.

Table 1. Statistical data for Ethiopia.

Total population (2012)	91,729,000
Gross national income per capita (PPP international $, 2012)	1,110
Life expectancy at birth m/f (years, 2012)	62/65
Probability of dying under five (per 1000 live births, 2012)	68
Probability of dying between 15 and 60 years m/f (per 1000 population, 2012)	250/212
Total expenditure on health per capita (Intl $, 2012)	44
Total expenditure on health as % of GDP (2012)	3.8

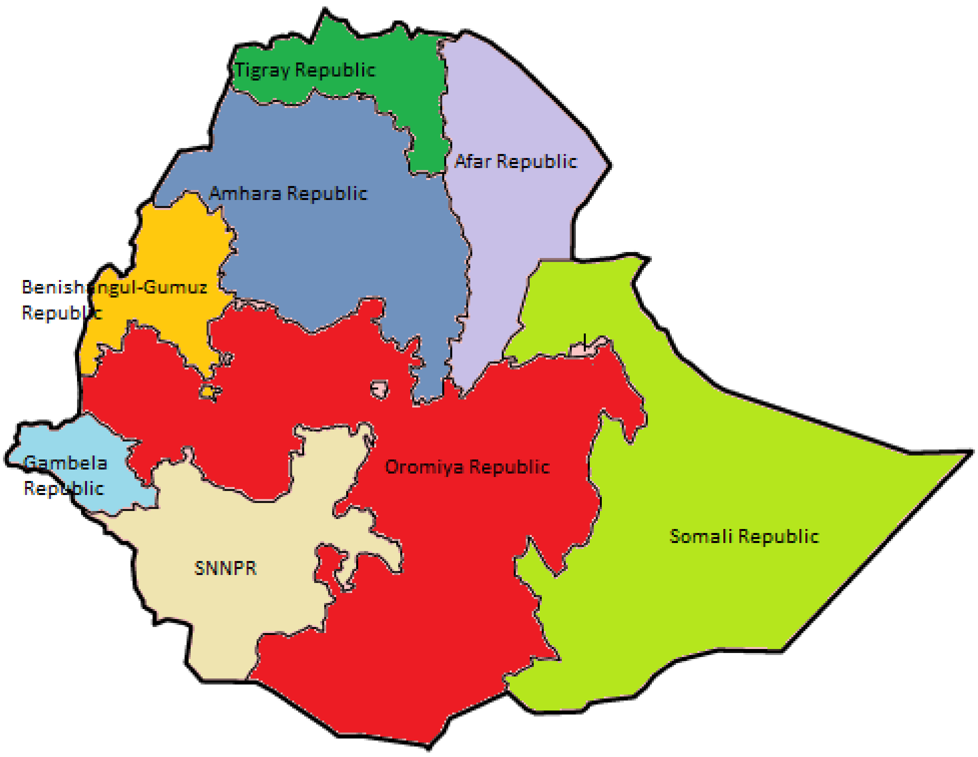


Figure 1. Administrative regions of Ethiopia.

2. Study site

In this research, the feasibility of solar photovoltaic water pumping system was studied selecting one potential site from three administrative regions of Ethiopia. The regions selected are Amhara, Oromia and Tigray regions. From the Amhara region Siadeberand Wayu was selected (latitude 9°46' N, longitude 39°40' E and altitude 3009 m a.s.l); from the Oromia region Wolmera was selected (latitude 9°13' N, longitude 38°39' E and altitude 2400 m a.s.l); and from Tigray region Enderta was selected (latitude 13°48' N, longitude 39°55' E and altitude 2247 m a.s.l). The solar radiation data for the three selected sites were collected from NASA-SSE satellite data (https://eosweb.larc.nasa.gov/sse/) and then imported to PVsyst software database using its meteorological tool. The monthly average solar irradiation values on horizontal surface for the selected three sites are shown in Figure 2, 3 and 4.

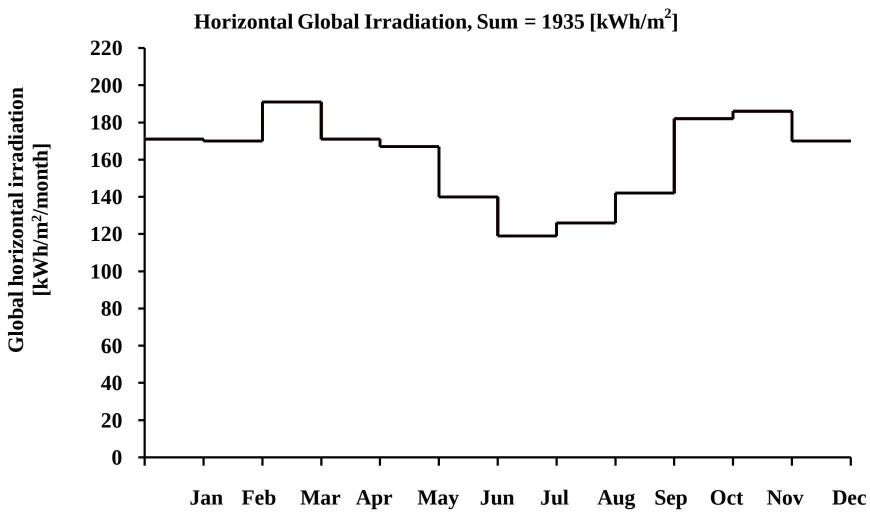


Figure 2. Year-long solar irradiation data for Siadeberand Wayu Woreda.

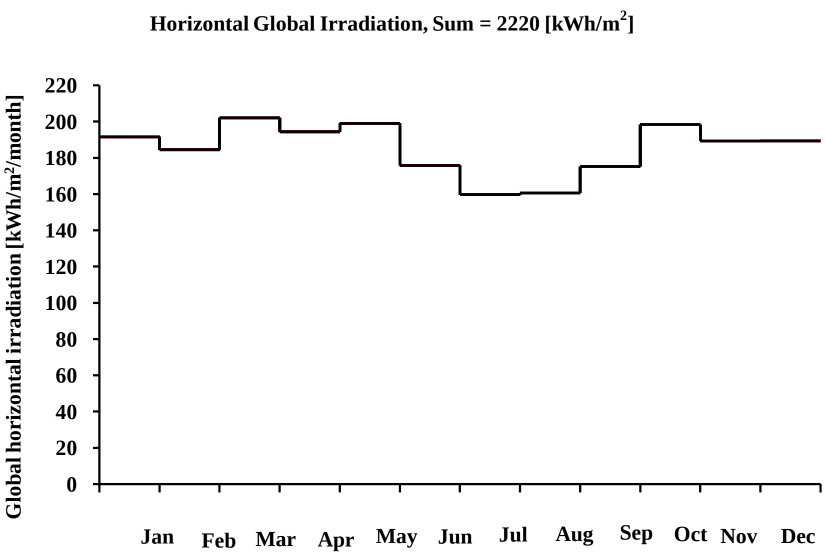


Figure 3. Year-long solar irradiation data for Wolmera Woreda.

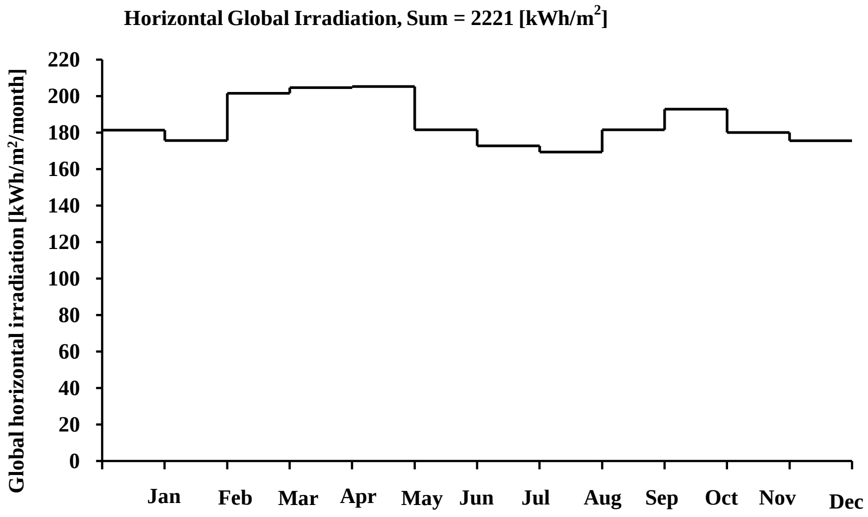


Figure 4. Year-long solar irradiation data for Enderta Woreda.

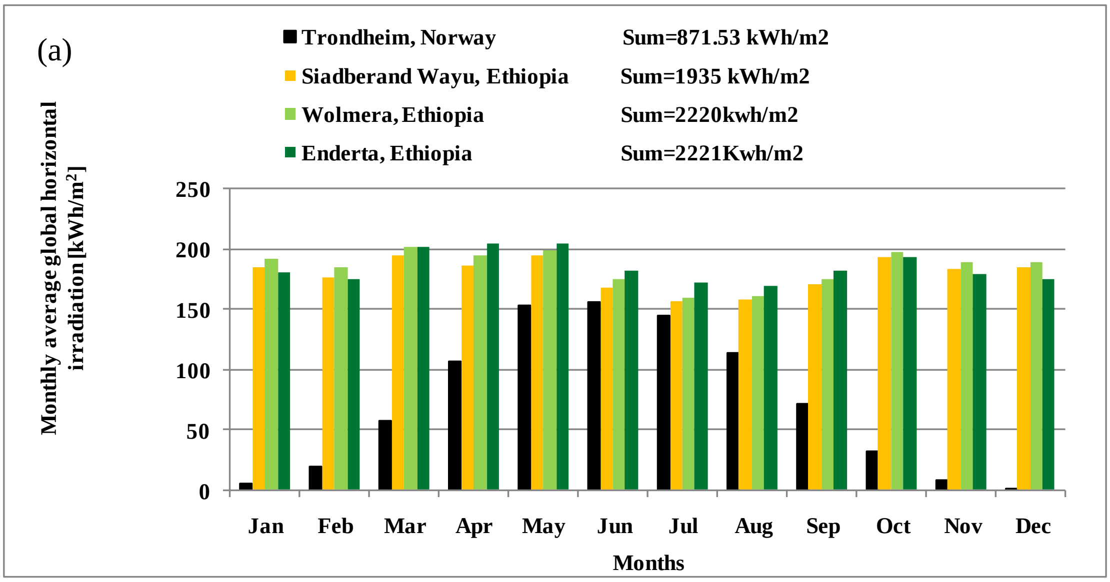
2.1. Solar radiation comparisons between Ethiopia and Norway

Ethiopia has huge potential for solar energy because it is located near the equator with an average daily solar radiation of 5.25 kWh/m^2 [16, 17]. The government of Ethiopia (GOE) with the collaboration of Chinese government prepared solar and wind master plan for the whole country, which can be very useful to identify the gross amount and distribution condition of wind and solar energy resources in the country. Based on the analysis of this master plan Ethiopia has a capacity of 1350 GW of energy from wind and annual total solar energy reserve of 2.199 million TWh/annum [18].

Norway is one of developed country in the world and has limited resources in solar energy, but is one of the world's largest producers of solar grade silicon and silicon cells [19]. In this study, Trondheim (latitude 63°36' N and longitude 10°25' E) was selected for comparison. The monthly average global horizontal irradiation data for Trondheim was collected from NASA-SSE satellite data (https://eosweb.larc.nasa.gov/sse/).

Figure 5a show that the global horizontal irradiation between the selected three sites (Ethiopia) and Trondheim (Norway).

According to Figure 5a the global horizontal irradiation in Ethiopia is high in the summer season (October up to May) and decreases in the winter season (June up to September). However, the global horizontal irradiation is uniform throughout the year in all selected sites. In case of Trondheim the global horizontal irradiation has significant variation in the year. Based on Figure 5a Ethiopia has higher global horizontal radiation than Norway. Therefore, not only water pumping but many other solar powered projects can be applicable in Ethiopia. In addition, Figure 5b below show that the monthly average global radiation difference between Endrta (Ethiopia) and Trondheim (Norway).



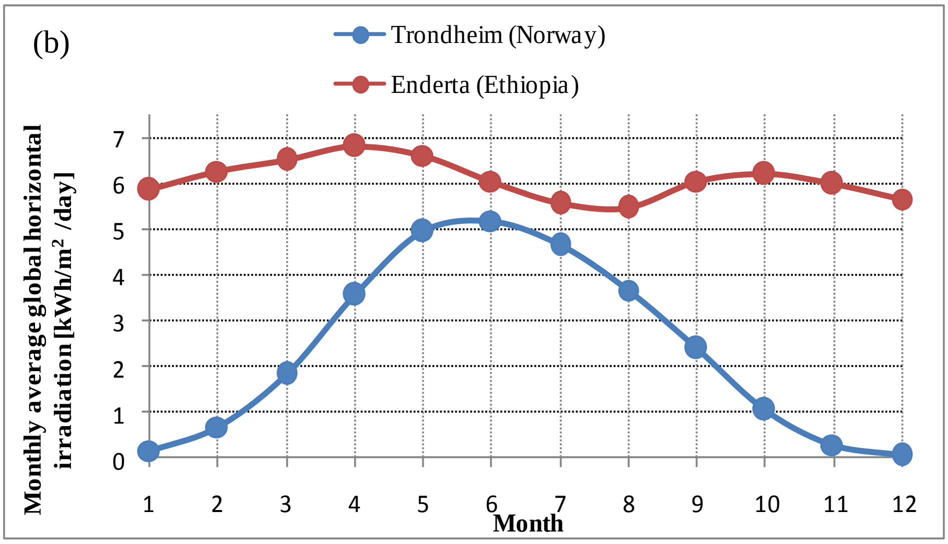


Figure 5. (a) Global horizontal irradiation comparison between study Areas (Ethiopia) and Trondheim (Norway); (b) Monthly average horizontal irradiation comparison between Enderta (Ethiopia) and Trondheim (Norway).

3. Solar photovoltaic water pumping system design and simulation

During the design and simulation process of SPV system, it is assumed that the solar panels are not shaded with free horizon and the simulations are performed based on the maximum possible annual water demand. The pump and solar panels are selected from the PVsyst software database to meet the maximum possible annual demands. However, based on available solar irradiation data for the sites, it is assumed that missing water will be up to 5%. The main design and simulation parameters are listed in the Table 2.

Table 2. Simulation input parameter for the three selected sites.

Parameters	Siadeberand Wayu	Wolmera	Enderta
Water requirement per day	10.5m^3/day, two days autonomy	7 m^3/day, two days autonomy	6.5 m^3/day, two days autonomy
Total head	37 m	100 m	76 m
Water storage tank volume	21.5m^3	14 m^3	13 m^3
Well depth	58 m	47 m	43 m
Borehole diameter	15 cm	15 cm	15 cm
Pipe length	300 m	450 m	376 m
Tilt	15 º	15 º	15 º
Azimuth	0 º	0 º	0 º
Solar panels type	Model:GES-5M5, 5W, si-mono, Manuf. Sainty solar	Model:GES-5M5, 5W, si-mono, Manuf. Sainty solar	Model:GES-5M5, 5W, si-mono, Manuf. Sainty solar
Pump type	Model: PS20-HR-07-MPPT, 300W, 48V, Manuf. Lorentz	Model: PS20-HR-04-MPPT, 240W, 48V, Manuf. Lorentz	Model: PS20-HR-07-MPPT, 300W, 48V, Manuf. Lorentz
Power conditioning	Direct coupling	Direct coupling	Direct coupling

4. Direct couple solar pumping system

In this study direct coupling method is used for the system power configuration. In direct-coupled pumping systems, electricity from the PV modules is sent directly to the pump, which in turn pumps water through a pipe to where it is needed. This system is designed to pump water only during the day. The amount of water pumped is totally dependent on the amount of sunlight hitting the PV panels and the type of pump. Because the intensity of the sun and the angle at which it strikes the PV panel changes throughout the day, the amount of water pumped by this system has also changed throughout the day [20].

Direct-coupled pumping systems are sized to store extra water on sunny days so it is available on cloudy days and at night. Water can be stored in a larger-than-needed watering tank or in a separate storage tank and then gravity-fed to smaller watering tanks. Water-storage capacity is important in this pumping system. Two to five days' storage may be required, depending on climate and pattern of water usage [20]. A layout of the solar photovoltaic water pumping system is indicated in Figure 6.

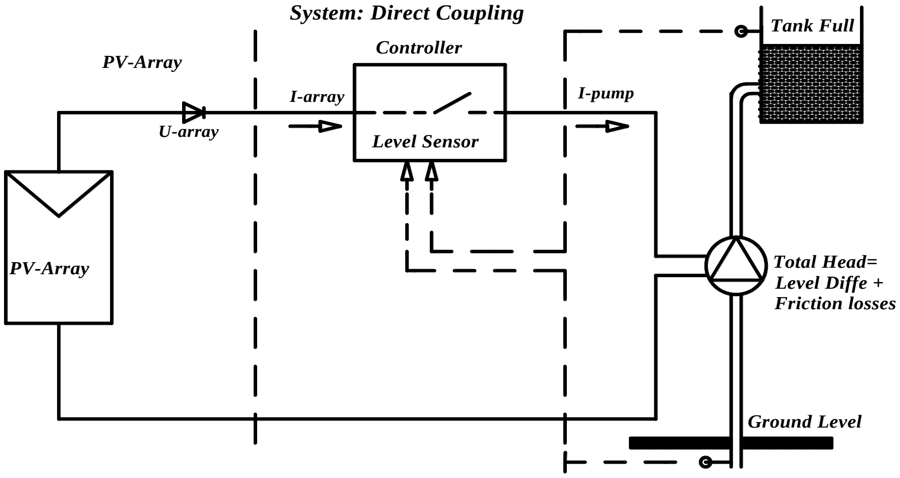


Figure 6. Schematic representation of the Solar-PV system providing power to a water pump.

5. Methodology

The solar pumping system mainly consists of PV array, solar pump and controller. In this study, and direct coupling method is used for power conditioning of the system. The target population is selected from three different regions of the country that is from Amhara region Siadberand Wayu site, from Oromia region Wolmera site and from Tigray region Enderta site consisting 700, 467 and 433 rural communities with daily average water Demand 10.5, 7 and 6.5 m^3/day respectively. And approximate average daily water consumption of 15 liters per day per person was taken. Figure 7 below shows the Schematic diagram of solar water pumping system.

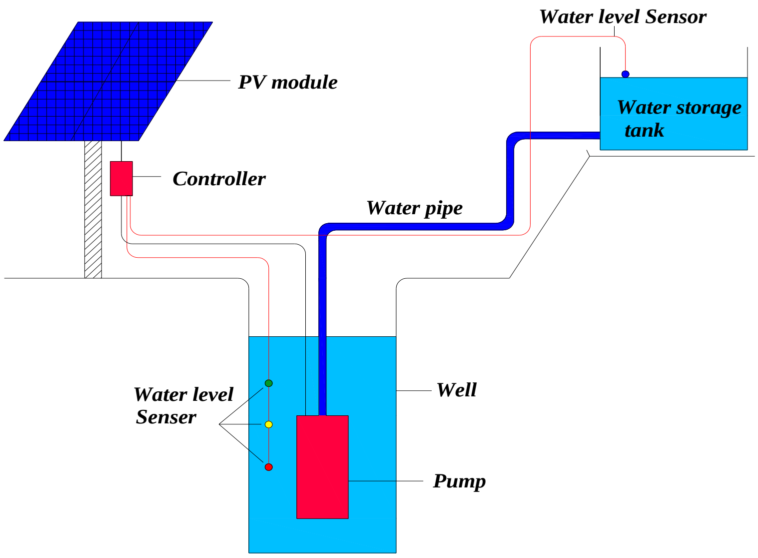


Figure 7. Schematic diagram of solar water pumping system.

There are different software's that can be applicable for solar photovoltaic water pumping system. In this research, however, PVsyst 5.56 has been used to simulate the solar photovoltaic water pumping system. The inputs of this software are monthly average solar irradiation, average daily water demand, well depth characteristics, selection of PV modules and pump. The simulation process on PVsyst software operates on hourly values.

During simulation analysis using PVsyst software the following points should be considered. The initial point is determining the global effective irradiation and the maximum power point (MPP), once irradiation and MPP determined, the simulation is dependent on the Pumping Type and Configuration [21].

For any running hour, the simulation has to determine the Flow rate delivered by the pump, as a function of the Head and the available electrical energy. The simulation has to manage the situations where the tank is full (limiting the pump's flow at the user's draw, and stopping the pump during the rest of the hour), and when the tank is empty. For obtaining a consistent balance, all energies should be carefully accounted for, in any running situation [21].

The final relevant results include mainly the water delivered to the users, the missing water, the excess (unused) PV energy, and the system efficiency during the year (or performance ratio). And, if economical features are defined, the global investment, yearly costs and cost of the water pumped in m^3 determined. After running the simulation for the selected sites based on input parameters for each site the following results are obtained.

6. Simulation Results

The main simulation results for the Amhara Region, Siadbere andWayu site, the Oromia Region, Wolmera site and the Tigray Region, Enderta site are shown in Table 3, 4 and 5, respectively.

Table 3. Simulation result for Amhara region, Siadbere and Wayu site.

PV size	5 W_p, 100 modules, 4 in series and 25 in parallel
Total area	10.1 m^2
Pump power	300 W, 48 V, well DC progressive cavity, 1 pump
Water pumped annually	3639 m^3
Missing water	5%
Energy at pump	2180 kWh
Unused energy	60 kWh
System efficiency	75.2% (global system efficiency or performance ratio)
Pump efficiency	20.1%
Water pumped	Average 9.97 m^3/day, and minimum 8.26 m^3/day in July
Maximum loss of load within the year	21.29% in July

According to the simulation result shown in Table 3, the selected PV size and pump power is able to provide 95% of water need for the community of Siadber and Wayu site. From May up to September there is a reduction of water supply, during the month of July there is a significant water supply reduction 21.29% and in May there is 0.49% water supply reduction.

Table 4. Simulation result for Oromia region, Wolmera site.

PV size	5 W_p, 68 modules, 4 in series and 17 in parallel
Total area	6.9 m^2
Pump power	240 W, 48 V, well DC progressive cavity, 1 pump
Water pumped annually	2465 m^3
Missing water	3.55%
Energy at pump	1553 kWh
Unused energy	0.0 kWh
System efficiency	70% (global system efficiency or performance ratio)
Pump efficiency	24%
Water pumped	Average 6.753 m^3/day, and minimum 6.106 m^3/day in July
Maximum loss of load within the year	12.8% in July

Table 5. Simulation result for Tigray region, Enderta site.

PV size	5 W_p, 88 modules, 4 in series and 22 in parallel
Total area	5.8 m^2
Pump power	240 W, 48 V, well DC progressive cavity, 1 pump
Water pumped annually	2284 m^3
Missing water	3.7%
Energy at pump	2002 kWh
Unused energy	0.0 kWh
System efficiency	70.1% (global system efficiency or performance ratio)
Pump efficiency	36.5%
Water pumped	Average 6.258 m^3/day, and minimum 5.939 m^3/day in July
Maximum loss of load within the year	8.7% in July

The selected PV size and pump power for the Oromia Region, Wolmera sites capable of providing 96.5% of water need for the community, Table 4. From May to October, there is a reduction of water supply and during the month of July there is a significant water supply loss of 12.8%.

The simulation result shown in Table 5 reveals that the proposed PV size and pump power is able to provide 96.3% of water need for the community of Enderta site. During the month of July there is significant water supply loss of 8.7%.

Figure 8, 9 and 10 show the energy balance of the proposed solar Photovoltaic water pumping system for the Amhara Region, Siadbereand Wayu site, the Oromia Region, Wolmera site and the Tigray Region, Enderta site. As can be observed from the figures, the unused energy is very low for all sites. This is because, the system is designed based on the maximum possible water production volume within the year.

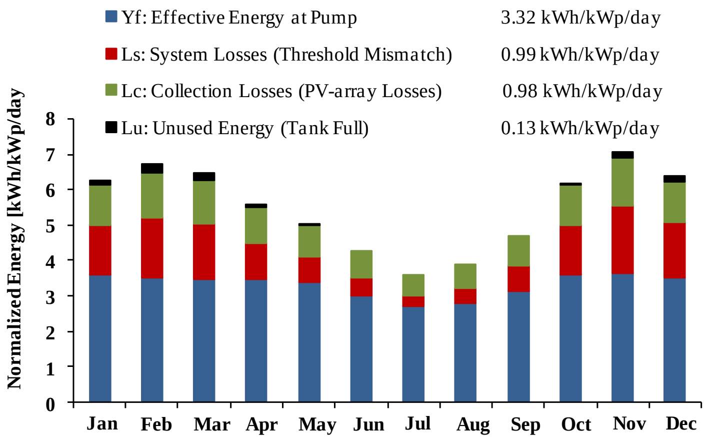


Figure 8. Energy balance of the SPV system for Siadberand Wayu site.

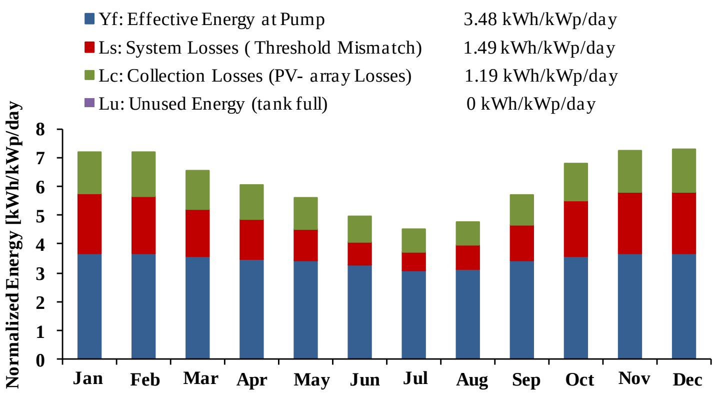


Figure 9. Energy balance of the SPV system for Wolmera site.

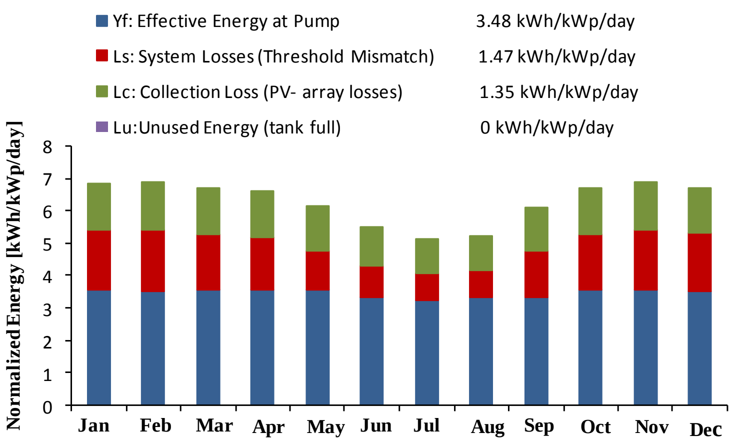


Figure 10. Energy balance of the SPV system for Enderta Woreda site.

The above three figures shows the normalized values of, effective energy at pump, collection loss, system loss and unused energy (tank full) in the system.

As we have seen from the figures the unused energy in the system for all sites are minimum and the system and collection losses are seems a little bit higher. This is because the system is designed to pump maximum possible amount of water per day using all available energy on the system. When the production maximized the system subjected to high losses, but if we reduce the amount of water pumped by the system per day, we can minimize the losses but the unused energy in the system will be maximize.

Figure 11 show the function of flow rate with respect to pump power. Since all graphs for all sites have similar behavior, only the graph of the Siadberand Wayu site has been presented here.

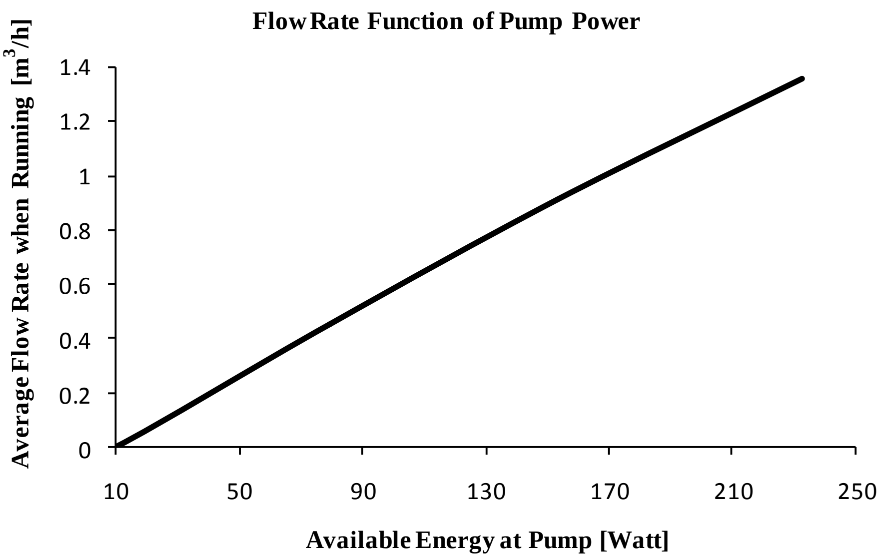


Figure 11. Flow rate function of pump power graph for Siadberand Wayu site.

Figure 11 shows the linear relationship between the flow rate and available energy at the pump. In addition, this figure indicates that how the size of pump depend on available power. If the available power at the pump varies the size of the pump or the flow rates also vary. Therefore, pump controller play a great role for adjusting the size of the pump according to the available power at the pump. Without pump controller it is impossible to operate solar pumps.

7. Economic analysis of SPV water pumping system

The economic analysis of solar photovoltaic water pumping system has been assessed using PVsyst software. A detailed economic analysis has only been shown for Siadberand Wayu site and summary of the economic analysis for the three sites is given in Table 6. During economic evaluation, the following approximate values have been considered.

7.1. Economic analysis for Siadberand Wayu site using PVsyst

Investment: (all costs below taken from manufacturer web-page based on the specification of components]

PV module cost: 100 units of 5 Wp = 0.896 $/Wp (20 year life span assumed)

Supporting / Integration: 0.5936 $/piece (one support for each module assumed)

Pump cost, including controller: 1 unit of 300W = 1523.88 $/piece (10 year life span assumed)

Setting and wiring. etc.: 20% of the subtotal cost is assumed (multiply the subtotal cost by 0.2 to cover the balance of the system)

Running costs (including pump replacement after 10 years) = 5% of the subtotal cost is assumed (includes provision for pump replacement after 10 years and maintenance cost)

Net Investment for Siadberand Wayu site**:** Sum of the above listed investment costs plus 15% tax = 3001.9$

Assuming a loan period of 20 years and interest rate of 5% with annual factor of 8.02%, the annuity (yearly cost without including the running costs) is equal to 241 $/year, and the total yearly cost including the running costs (maintenance, taxes and replacement costs) is equal to: 372 $/year.

Based on the above data, the water cost is equal to 0.1 $/m^3, without any subsidies.

If 20% subsidy by the government is assumed to motivate internal and external investors, the cost of the water will reduce to 0.09 $/m^3.

Similar economic Analysis is carried out using PVsyst software for the other two sites and the values are given in Table 6 below.

Table 6 includes the economic analysis results of the PVsyst software for the three selected sites. The table includes the net investment cost, annuities, total yearly cost and water cost with and without any subsidy. Annuities without any subsidy mean annual cost without including the running costs and subsidization from the government or any other organization. And the difference between annuities and total yearly cost is the total yearly cost includes the running costs of the system but annuities does not include. Based on the input parameter, the water cost per m^3 for each sites are calculated using PVsyst software and included in Table 6.

Table 6. Summary of economic evaluation using PVsyst software for the three sites.

Site	Net Investment ($)	Water Pumped (m^3/year)	Annuities without any subsidy ($/year)	Total Yearly Cost ($/year)	Water Cost without any subsidy ($/m^3)	Water Cost with 20% subsidy ($/m^3)
Siadberand Wayu	3001.9	3639	241	372	0.1	0.09
Wolmera	2691.1	2465	215.95	345	0.14	0.13
Enderta	2832.7	2284	227.31	355.23	0.16	0.15

8. Financial comparison for SPV and diesel pumping system

In the financial comparison between solar photovoltaic and diesel water pumping, the main question is how the financial costs of both systems can be calculated. The whole costs of a pumping system have a certain life expectance in years that is made up of the capital cost, operating cost and maintenance and replacement cost (M & R). And these costs altogether refer to the life cycle cost (LCC) [14, 23-25]. The life-cycle cost can be calculated using the following formula:

$$LCC = CC + M_{PC} + E_{PC} + R_{PC} + S_{PC} \quad (1)$$

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

The Maintenance Cost (MC) 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:

$$MC = A * \left[\frac{(i+1)^N - 1}{i*(i+1)^N}\right] \quad (2)$$

Where, *A* is the annual worth

i interest rate

N life cycle time (year)

The Energy Cost (EC) of a system is the sum of the yearly fuel cost. Therefore differential fuel inflation rates may be used. Fuel cost through the life time of the system is calculated using this equation:

$$EC = A * \left[\left(\frac{1+FE}{i+FE}\right) * \left(1 - \left(\frac{1+FE}{1+i}\right)^N\right)\right] \quad (3)$$

Where, *FE* is the fuel escalation rate

This equation belongs only to diesel engine life cycle cost of fuel. Because there is no energy cost considered in case of PV system.

The Replacement Cost (RC) is the sum of all equipment that will need to be replaced through the life of the system.

Pump for the PV water pumping system assumed to be replaced after 10 years and all components of the diesel pumping system also have to be replaced after 10 years. The total replacement cost through the life time is calculated using this equation:

$$RC = F * \left[\frac{1}{(i+1)^N}\right] \quad (4)$$

Where, *F* is the future worth of money

The Salvage Value (SC) 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:

$$SC = F * \left[\frac{1}{(i-1)^N}\right] \quad (5)$$

Where, *F* is the future worth of money

The cost comparison using the LCC method between the SPV and DP systems for the Siadberand Wayu site was shown in Figure 10 below. Figure 11 also shows that the present cost comparison between the SPV and DP. In addition, the cost of m^3 of water for all sites is compared with diesel system and the result was shown in Table 10.

For the analysis of a 20 year life cycle cost comparison between SPV and DP for Siadberand Wayu site the following assumptions are considered.

The operating life of the PV panel was assumed to be 20 years and for the diesel engine 10 years were assumed.

The maintenance cost of a PV system assumed to be a 1% of total capital cost per year.

Available sunshine hours 2190 hours considered in a year, The available sunshine hour's data from national metrology agency of Ethiopia indicates an average sunshine hour in Siadberand Wayu varies from 4.65 hr in July up to 9.42 hr in November, and the annual average sunshine hour's is 7.77 hr/day. Therefore, for this analysis 6 hr/day working time was assumed for the system to provide the required daily water demand.

Maintenance cost of diesel engine assumed to be a 10% of total capital cost per year.

Cost of 500 Wp diesel generator = $200 and its consumption of diesel fuel is assumed to be 0.20 L/hr.

The diesel generator can be selected based on its maximum output (Kilowatt). During selection of the diesel generator, it is important to select the one whose output power is slightly higher than the total power needed, to be sure the generator will supply enough power for the pump.

Operating hours = 6 hr/day (similar as solar pumping)

Current price of diesel fuel in Ethiopia is 0.805 $/liter.

The replacement costs are evaluated to be once during the life analysis for diesel generator.

The pump and storage tank cost is not included in the analysis because the costs are assumed to be equal for both systems.

Salvage value of diesel engine was assumed to be a 20% of capital cost of engine. And for PV module 5% assumed.

The pump, storage tank and distribution line costs are not included in this analysis because, it is considered as the same for both case

$$\begin{aligned} &Annual\ Fuel\ Cost \\ &\quad = Specific\ Fuel\ Consumption * \ Total\ Operating\ Hours\ in\ a\ Year * Fuel\ rat \\ &\quad = 0.20 liter/hr * (6hr/day * 365\ day/year) * 0.805\ \$/liter = 352.6\$/year \end{aligned}$$

$$Fuel\ Cost\ of\ Diesel\ Generator\ for\ 20\ years = 20\ Year * 352.6\ \$/year = 7052\ \$$$

Table 7 shows the cost comparison between the SPV and DP water pumping system using life cycle cost analysis method for the Siadberand Wayu site.

Table 7. SPV and DP system cost comparison using LCC for Siadberand Wayu site.

Costs ($)	PV system ($)	Diesel Generator ($)
Capital cost (CC), the pump cost is not included	1126.72	200
Maintenance cost (MC)	225.34	400
Fuel/Energy cost (EC) for 20 years	None	7052
Replacement cost (RC) for generator	None	200
Total cost	**1352**	**7852**
Salvage value (SC)	56.34	40
Life cycle cost (LCC)	**1295.66**	**7812**

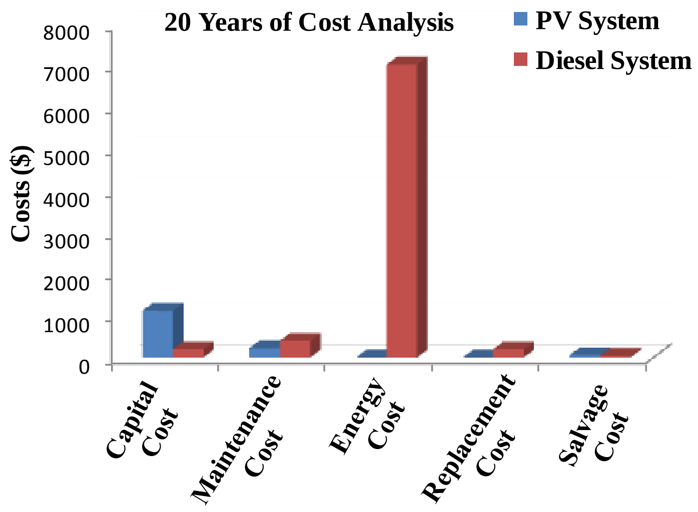


Figure 12. Cost Comparisons of PV System and Diesel System for pumping water.

As shown in Figure 12 above, the diesel powered pumping system has lower initial cost than the PV pumping system, but its other costs are higher if we compare with PV system. In the reveres, the initial cost of PV systems is high, but the maintenance, operation and replacement costs are lower. In addition, there is no energy cost needed in PV system and as a result the present cost of PV systems is much lower than the diesel powered system as shown in Figure 13. Its lower operation and maintenance costs, the longer expected useful life as well as the higher reliability of PV systems could make the system more suitable for remote areas. As shown in Figure 12 & 13 the operation, maintenance and fuel cost are higher for the diesel system, now a day the fuel price is increasing all over the world, so these numbers keep going up. The Present cost of both systems throughout the 20 years life cycle Analysis was shown in Figure 13 below.

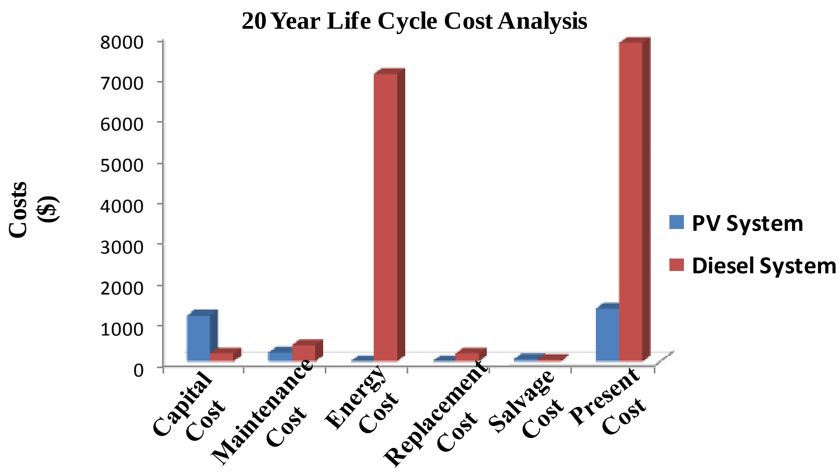


Figure 13. Present Cost Comparisons of PV and Diesel Pumping System.

8.1 Cost of pumping water

The cost of m^3 of the pumped water by PV water pumping system was calculated by PVsyst software in the previous section but the cost of m^3 of water for diesel water pumping system is not calculated. Therefore, the cost of m^3 of the pumped water by diesel water pumping system is calculated using the cost annuity method based on the LCC analysis [20, 27]:

$$Cost\ of\ m^3\ of\ water\ pumped\ = \frac{Annualised\ \ life\ cycle\ \ cost\ of\ the\ system}{Total\ \ pumped\ \ water} \tag{6}$$

The annualized life cycle costs are calculated from the relations:

$$\mathrm{CRF} = \frac{\mathrm{d}}{1-(1+\mathrm{d})^{-\mathrm{N}}} \tag{7}$$

$$PWF = \frac{1}{(i+1)^N} \tag{8}$$

$$C_y = C * CRF \tag{9}$$

$$C_K = R_K * PWF \tag{10}$$

$$R_y = \sum_K C_k \tag{11}$$

$$A_y = C_y + M_y + R_y \tag{12}$$

Where: *PWF* is the present worth factor
CRF: capital recovery factor
d: discount rate
N: lifetime period
i: interest rate
$C_{y:}$ annualized capital cost
C_k: present worth of replacement at year k
R_k: cost of replacement of the a system component at year k
R_y: present worth of all replacements incurred during the lifetime N
M_y: yearly operating and maintenance cost of the initial capital cost C
A_y: annualized life cycle cost

The above formulas are taken from a book with title “Fundamentals of Engineering Economics” by Chan S. Park and from pdf document with title photovoltaic pumping system (link.springer.com/content/pdf/10.1007%2F978-1-4471-2403-0_6.pdf). Table 8 includes different assumptions that were made during cost comparison between solar and diesel water pumping system**.** Table 9 shows the total initial gross investment cost of PV and diesel water pumping system and Table 10 shows the cost of pumping m^3 of water using PV and Diesel water pumping systems for three sites. Based on the annual life cycle cost, the PV water pumping system is more economical than the Diesel system.

Table 8. Economic assumptions for all sites.

Parameters	Siadberand Wayu	Wolmera	Enderta
Interest rate (%)	5	5	5
Discount rate (%)	10	10	10
Life time of PV generator(years)	20	20	20
Life time of motor-pump(years)	10	10	10
Life time of diesel generator(years)	10	10	10
PV unit cost ($/w$_p$)	0.896	0.896	0.896
Diesel fuel cost ($/l)	0.805	0.805	0.805
PV operation and maintenance (%)	1	1	1
Diesel operation and maintenance (%)	10	10	10

Reference for PV-module price (http://www.pvmagazine.com/investors/module-price-index)

Table 9. Total initial gross investment cost of PV and diesel system ($).

pump	Siadberand Wayu	Wolmera	Enderta
PV module			
Total cost of the Module	432	293.76	380.16
Cost of motor-pump	1523.88	1523.88	1523.88
Support structure cost	57.24	38.92	50.37
Wiring and Other miscellaneous	597.24	482.98	508.25
Total initial cost for PV	2610.36	2340.12	2462.66
Diesel system			
Unit cost	200	200	200
Total initial cost for Diesel	1723.88	1723.88	1723.88

Table 10. Annuity and water cost calculation for the PV and diesel system ($).

pump	Siadberand Wayu	Wolmera	Enderta
PV			
Annualized capital cost	306.72	274.96	289.4
Operation and maintenance cost	19.56	18.18	19
Replacement cost	46.76	46.76	46.76
Annualized life cycle cost for PV system	373.04	339.91	355.23
Water cost for PV system ($/m^3)	0.1	0.14	0.16
Diesel			
Annualized capital cost	202.6	202.6	202.6
Operation and maintenance cost	20	20	20
Replacement cost	105.85	105.85	105.85
Annual Fuel cost	352.6	232.3	290.37
Annualized life cycle cost for Diesel system	681.05	560.75	618.82
Water cost for Diesel system ($/m^3)	0.2	0.23	0.27

9. Conclusion

In this paper, the feasibility of solar photovoltaic water pumping system has been investigated for three selected sites in Ethiopia. The designed system is capable of providing a daily average of 10.5, 7 and 6.5 m^3/day for 700, 467 and 433 rural communities in Siadberand Wayu, Wolmera and Enderta sites, respectively, with average daily water consumption of 15 liters per day per person. And the cost of water, without any subsidy, are approximately 0.10, 0.14 and 0.16 \$/$m^3$for Siadberand Wayu, Wolmera and Enderta sites, respectively. If a 20% subsidy is considered during simulation, the cost of water would reduce to 0.09, 0.13 and 0.15 \$/m^3, respectively.

If Diesel generator is used instead of SPV water pumping system, providing daily average water 10.5, 7.0 and 6.5 m^3/day for 700, 467 and 433 rural communities in Siadberand Wayu, Wolmer and Enderta sites, with average daily water consumption of 15 liters per person, the cost of pumping water, without any subsidy, are approximately 0.2, 0.23 and 0.27 \$/m^3 for the respective sites.

The life cycle cost analysis of pumping water shows that the SPV water pumping system is more economical and feasible compared to Diesel system. The results indicate that more SPV systems can be installed in the country, replacing the existing more expensive Diesel systems, which would play significant role in achieving the country's MDG targets.

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Conflict of Interest

All authors declare no conflict of interest in this paper.

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