APPLICATION OF A PHOTOVOLTAIC SYSTEM IN WATER PUMPING

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ABSTRACT

Supply of commercial type of energy sources for rural communities has been a problem, especially in least developed countries like Ethiopia. With a sizeable percentage of its population living in the rural areas on predominantly centuries old and unproductive farming practices, cyclic draught and limited foreign currency earning export have resulted in lack of food security in the Country. To modernize the agricultural activities and achieve a better standard of living, the need for a viable type of energy resource base for the rural communities is highly critical.

In this paper the energy from the sun through the use of the Photovoltaic system for water pumping is explored. The PV system at two pumping sites: one for potable water supply and the other for irrigation purposes have been monitored for four years under real operating environment. The daily water volume pumped by the PV system of 1.6 Kw_p has been compared with diesel, wind and hand pump systems and found to be a viable alternative. The 0.6 Kw_p PV float type pump used for irrigation can easily irrigate 4.5 hectares of land and the users be able to pay back the investment cost within 2 to 3 years.

Although the PV system has a high initial investment cost, this alone shauld not necessarily be taken as a deterrent for its utilization. Its other direct and indirect benefits, foreseeable cost reduction, ease and security of usage, possibility of system expansion by simply adding modules makes the PV system as one of the strong alternatives for satisfying the energy demands of rural communities.

INTRODUCTION

The per capita use of energy in a country does have a strong resemblance to its standard of living. The more use of commercial type of energy sources (like fossil fuels, hydro power and nuclear energy) the better is the standard of living or the wealth of a nation. For example, the per capita commercial type of energy use for.

USA.........................10. 240 tce
Ethiopia........... ....26 tce
World's Average.........1893 tce
tce (ton coal equivalent) = 2.9 X 10^{10} J

The indicated per capita energy consumption of Ethiopia is the lowest in the World If we also look at the world's energy mix and compare with that of Ethiopia,

World	**Ethiopia**
Oil - 41.8%	Fuelwood - 69.8%
Gas - 18.%	Animal dung/Agri-waste - 14.8%
Coal - 29.4%	Human + Animal (food equivalent) - 9.4%
Hydro - 6.8%	Charcoal - 1%
Nuclear - 3.3%	Oil - 4.2%
	Electricity - 0.8%

The commercial or modern type energy source (oil & electricity) usage in Ethiopia is about 5% and out of this close to 40% was consumed in Addis Ababa alone in 1984. The non-commercial type energy source (like fuelwood, agri-waste and animal dung) account close to 95%. The term non-commercial type energy source is used to denote that no proper investment or organized effort is made to actually harvest and continuously supply with a designated calorific value such kind of an energy source to a potential market. This dependence and high usage of the non-commercial type of energy source with low calorific value will continuously hamper the Country's development unless other forms of energy sources are provided that can give sufficiently high energy for motive power production that are suitable for both the agricultural and industrial sectors of the economy of the Country.

NEED FOR MOTIVE POWER

In order to understand the need for an energy resource base with high motive power in Ethiopia, one should first of all look at the prevalent socio-economic condition of the Country:

- The main source of income of the Nation is in agriculture and cattle breeding
- Farming is done by way of centuries old and traditional practices requiring intensive use of human labour and draft animal power, and
- The population growth rate is more than 3% per year.

What is evident at the moment is that the pressure caused by a rapid population growth rate, limited resource to acquire and prepare more arable land, a meagre use of the water resource potential for irrigation and unproductive employment especially in the rural areas have already forced a change in the mode of life of the rural setting and people have been flocking towards the city for better employment. Under normal circumstances, the trend should have been, as the productivity of the farms increase the labour force in the farms has to go to industries but unfortunately this is not the case. The need for more productive methods of farming with the use of mechanized power and developing irrigation schemes is very high

To improve the agricultural activities of the farmers and thereby raise the standard of living of the rural communities, among other things, there is a great need for

- Energy for high motive power production for the agricultural sector of the economy,
- Energy for cooking and lighting, and
- Energy for small scale industries

Ethiopia has a vast hydro power resource. With an installed power of about 366 Mw, what has been harnessed so far is less than 2% of the expected potential. Although the hydro power potential of the Country is high, the development cost of conventional type of hydro power plants (like Awash, Fincha and Melka Wakenna power stations) is very high and is not suitable for most of the rural settlements that exists. Such kind of hydro power plant is quite useful to satisfy the energy demands of larger cities (for lighting, cooking and industries). To satisfy the fast growing energy demand of the rural community, which may account to about 85% of the Nation, the alternative is to make an endeavour to employ decentralized technologies based on renewable energy resources.

The renewable energy resource base that could be employed to advantage for rural Ethiopia are solar energy, wind energy, small hydros, biomass and to some extent geothermal wells. The systems envisaged are decentralized systems (decentralization implies localized systems built for a task at hand), like photovoltaic plants, windmills, small hydro power plants, bio- gas plants, etc

THE PHOTOVOLTAIC SYSTEM

Ethiopia is endowed with an abundance of sunshine throughout the year. The insolation level ranges between 4.5 Kwh/sq.m/day to 7.2 Kwh/sq.m/day and with a yearly average of about 5.4 Kwh/sq.m/day. The daily and monthly variation of the insolation level is narrow enough for efficient utilization of solar energy conversion devices such as a photovoltaic system

Terrestrial application of the photovoltaic system started in the early 1970's as a response to the first oil crisis. Later in 1985, research and development in PV materials intensified especially in Europe after the Chernobyl nuclear accident. The application of the photovoltaic system varies from a single to communal use as well as to supplying energy to utility grids

Terrestrial photovoltaic systems can be categorised into three applications stand-alone, hybrid, and grid connected. Fig. 1 shows the block diagram representation of these systems.

The **stand-alone** system typically consists of a storage battery system and is employed in the supply of energy to remote areas with no electricity grid or a back-up system facility. Rural community electrification, village clinic or school or water pumping applications are the main types of loads. Both dc and ac types of loads are handled by the system and the Power Conditioning & Management (PCM) unit matches the array with the battery and the load. The charge/discharge controller circuitry for the battery, dc/ac inverter as well as the regulator and the necessary load management control circuits are also in the PCM.

The **hybrid** photovoltaic system consists of a back-up system like a diesel/gasoline generator. Such a system is usually applicable if there is a critical load in the system that needs uninterrupted supply of power. Since the system incorporates an additional energy source (generator) the cost of the system is on the high side.

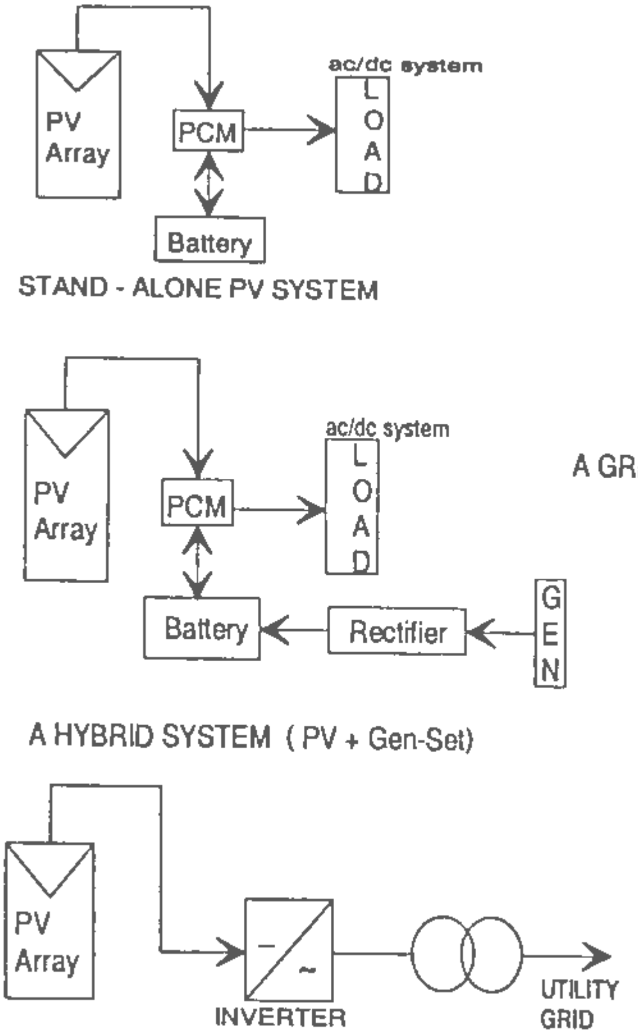


Figure 1 Block Diagram Representation of Terrestrial Photovoltaic systems

The **grid-connected** or also referred to as cogeneration system is employed to feed the utility grid with PV generated electricity. In this system the utility grid acts as an infinite energy sink and the inverter circuit matches the PV output to the grid.

PHOTOVOLTAIC SYSTEM IN WATER PUMPING

Photovoltaic systems were mostly used for space application before the early seventies. After the first oil crisis of 1973, the application of the photovoltaic system for terrestrial use gathered momentum and developed rapidly. Many technological changes have been introduced in the manufacturing process to improve its versatility and also to reduce systems cost. A wide variety of applications ranging from a few microwatts (for watches) to hundred of kilowatts for stand-alone rural electrification systems have been tried. Generally, applications of a photovoltaic system are typically identified by their end use: Water pumping, water desalination, telecommunication, rural electrification, as well as in hybrid and central power plants. The principal factors affecting the efficient operation of a photovoltaic system are the solar irradiance level, ambient temperature, nature of the load, chosen system configuration and the resulting matching conditions of the array to the electronic control circuit, the battery and the load. The conditions under which solar arrays operate at a given location causes the dc power output of the array to vary over a considerable range from day to day and throughout the year. To overcome this problem, within a certain range of variations, the array output needs a conditioning sub-system that may include inverters, charge controllers, frequency controllers, maximum power point trackers, DC/DC converters as well as load management controllers before it can be usefully employed for most applications.

The stand-alone photovoltaic system is the most common system employed for electrification of rural communities, health centres and schools. For water pumping purposes, the system usually operates without a battery unit and is as shown in Fig. 2.

In Fig. 2a, the PV array is directly connected to the pump. Whenever there is sunshine the array generates a dc voltage which is directly connected to a dc motor and pump. Such a system is suitable for low head and high discharge application like an irrigation system and operates well for loads less than 1 Kw. The system configuration shown in Fig. 2b includes a dc/ac inverter unit. The inverter is useful in voltage regulation, runs an ac motor and may also include maximum power point tracker and frequency controller so as to make the array operate at its optimum power point for a range of insolation levels.

In photovoltaic water pumping the quantity of water delivered by the PV system depends on the insolation level reaching the array which may vary with seasonal changes, the head against which the water is to be pumped and the overall system performance. Commercially available PV water pumping systems are in a variety of configurations,

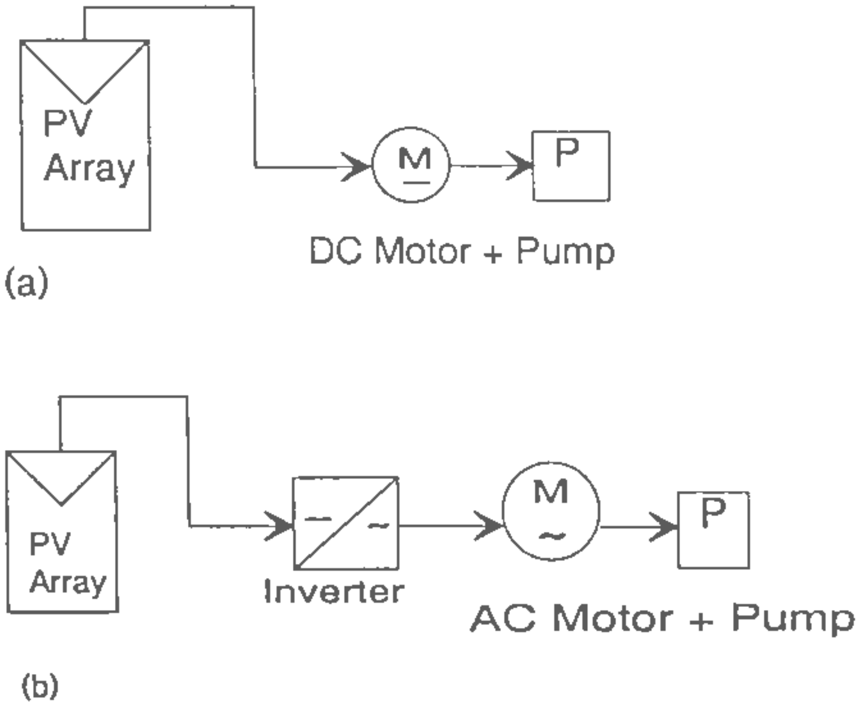


Figure 2 Photovoltaic System for Water Pumping Application

Two of the principal configurations are:

1. Submersible centrifugal motor/pump unit which is mostly used for village water supply system, and
2. Floating centrifugal motor/pump unit which is suitable for irrigation purposes.

Through the financial support of the Swedish Agency for Research Co-operation with Developing Countries (SAREC), the Electrical Engineering Department of the Addis Ababa University and the Research & Development Services of EWWCA have been running since December 1992 a photovoltaic water pumping project for potable water supply and irrigation purposes at Weg and Awash Melkassa, respectively. The following is a summary of the activities for the two pumping sites.

Site: WEG

POTABLE WATER SUPPLY SYSTEM

The site is about 175 Km from Addis Ababa, 7 Km from Ziwaye on the Ziwaye- Butajira road and about 5 Km off the road to the right.

System: PANEL + INVERTER + PUMP

1.6 Kwpeak, Kyocera 32 solar panels
(8s X 4p)
1.5 KVA Grundfos inverter
Pump - Grundfos SP5A - 10
The arrays make a tilt of 15^0S and face the equator.

Well Data . Total head 62m
Pump setting at 58.5m below ground
Reservoir capacity - 30 cu.m with four faucets for the supply of water
System's Cost is about USD 15,000.00 (excluding the reservoir)

Most arrays are generally designed to carry the modules at a fixed tilt angle which maximizes the amount of insolation received over the year. The best tilt angle is the latitude of the site and has to face the equator. However, the tilt angle should not be less than 15^0 to reduce dust accumulation. Generally, it is advantageous to have an array with a flexibility to adjust the tilt angle manually every few months so as to maximize the received insolation and reduce the array size.

System has been operational since December 1992 without any interruption and monitored by the daily water delivery against the total pumping head. Depending on the insolation level received, the flow rate changes proportionally. The pump starts between 8:00 and 9:00, reaches its maximum flow rate between 11:00 and 14:00 and stops at about 17:00. In the afternoons, although the insolation level received is high since the ambient temperature increases the system drops its flow rate due to the increase in the cells temperature of the array and in turn decreasing the efficiency of the system. The system operates for 8 to 9 hours daily and delivers on average about 12.5 cu.m. About 5000 persons are using the well and the per capita water consumption is less than 20 l.c.d. System is run by two persons whose main task is to guard and clean the panels, record water meter readings and collect money from users. The users have been made to pay 5 cents per 40l of water. A committee has been set up for the efficient operation of the system and the money collected is utilized for the salary of the two persons and for up keep of the system. Here it has to be noted that the cost for water by a family of 5 is about Birr 1.50 per month. This is by any standard too low considering the saving in time in fetching water from a river which is close to 7 Km one way. The time and labour saved in fetching water could be utilized in other productive work and the cost for water per family could even be raised to Birr 3.00 per month to cut down the system's pay back period.

Investment return in photovoltaic potable water pumping system just by the money saved direct through the sale of water is slow and would take a number of years to cover the system's initial expenditure. However, other indirect benefits through the use of potable water like saving energy and time that could be used for other productive purposes, use of clean water with improved health care and partially relieving the great burden of women and children (fetching water is part of their task in many families) should not be over looked.

The system installed is easy to operate and so far there has been no cost for maintenance. Acceptance of the system by the people is high and poses no danger to users at all. However, the initial investment on the system is quite high. With research and development in the semiconductors area, efficiency increase in the modules (less array size and cost) and over all reduction in production cost within the coming few years are quite inevitable, as witnessed in the cost reduction of panels in the past years.

Fig. 3 shows the monthly max, min and average water discharge from the borewell at weg. With an average discharge of about 12.5 cu.m of water per day the well has been supplying water to the villagers since December 1992 without fail

Site : Awash Melkassa

IRRIGATION SYSTEM

The site is 120 Km from Addis Ababa on Assela road and about 3 Km off the road towards the Awash river.

System . PANEL + DC FLOAT PUMP

600 Wpeak, Kyocera 12 solar panels
(4s X 3p), with a tilt of 15^0S
DC motor + Float type AQUASOL - 100 L pump
Head is about 3.75 m.
Water is from Awash river brought to the field by making a hand dug canal about 1Km in length, with 2m depth and 0.7 m width

System's total cost . USD 7,000.00

System has been operating since March 1993 without any failure. The daily water discharge is recorded by a pump attendant recruited from the farmers and the global insolation received has been monitored using an Eppley Pyranometer located in the compound of the Institute of Agricultural Research Office at Awash-Melkassa. The system delivers on average about 135 cu.m per day. This volume of water could irrigate 4.5 to 5.5 hectares of land especially in vegetable gardening. The system is needed for eight months in a year and for the remaining four, rain is used to grow mainly staple food crop.

Since the introduction of the solar irrigation pump in the community, some families have been busy during the sunny season of the year by growing vegetables for the market in Nazareth and have supplemented their yearly income greatly. During the eight months period, two harvests can be done. From a hectare of tomatoes a single family has collected Birr 9000.00 from a single harvest. At one moment there were 21 farmers using the pump; of course the land holding for most was a fraction of a hectare. The pump could irrigate 1.5 hectares of land per day and since the crop (typically tomatoes) needs watering every 3 days, the pump could effectively be used up to 4.5 hectares

From the experience gathered so far, it is possible to cover the system's cost within a few years. The problem at the moment is on how to get this sum of money for the initial investment A scheme has to be developed by the government to lend money to the farmers for such purposes without any collateral.

Regarding system's failure, since the system has only the solar panels directly connected to the dc pump, the component parts of the system are only two and the chance of failure is low. The solar panels would stay for a long time (over 20 years) without any considerable change in performance. The dc pump would need replacement after some time and its cost is about 30 - 35% of the initial investment. Without reaching this state the system would return its investment without any problem.

Fig. 4 shows the monthly max, min and average water discharge of the system. Under the present condition, this is shared by a group of farmers growing tomatoes and pepper and their total land holding is between 4 to 5 hectares. For vegetable gardening by compacting the canals to reduce seepage during the transport of water, it is possible to increase the hectarage.

APPRAISAL OF A PHOTOVOLTAIC PUMPING SYSTEM

Initial Appraisal of Systems

Since December 1992 the photovoltaic water pumping system at Weg has been operational in actual situations of usage in the field. No system's failure or performance deterioration have been recorded so far and the acceptance of the system by the people is very high. The photovoltaic unit has replaced a diesel mono-pump that had irregular

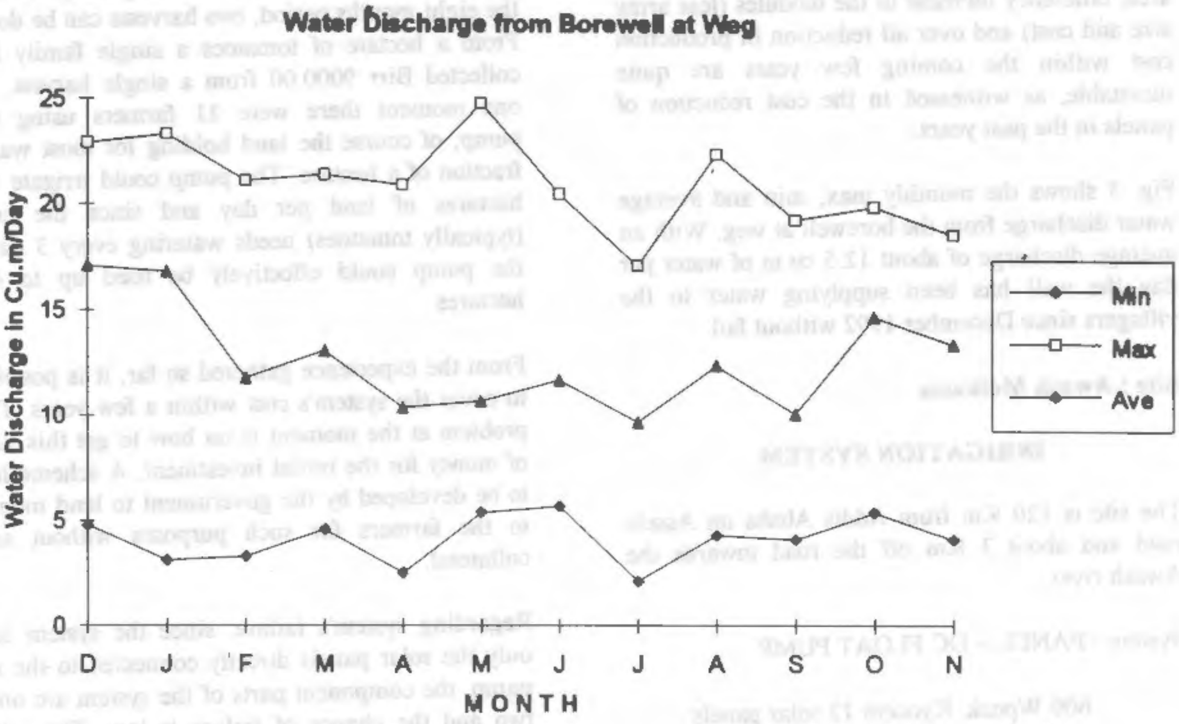


Figure 3 Water Discharge for Potable Use from Borewell at Weg

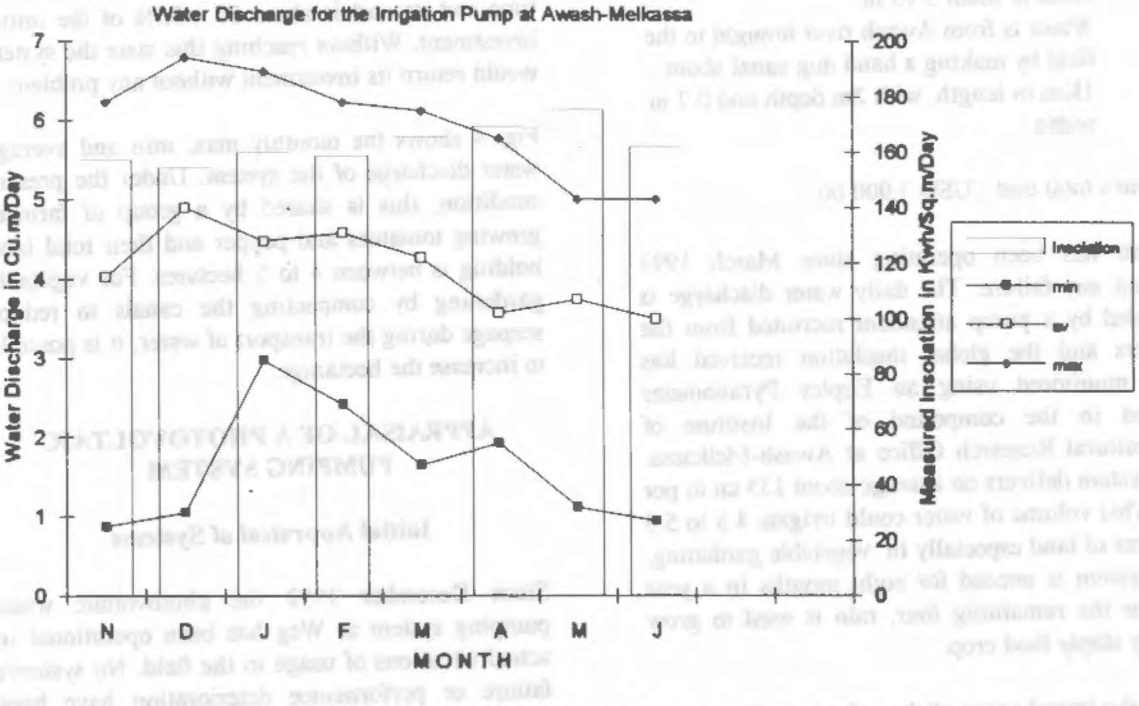


Figure 4 Water Discharge for Irrigation at Awash - Melkassa

operation due to shortage of supply of fuel and need for repair and maintenance. Earlier, the diesel system had replaced a wind pump system after the system had been torn apart by the wind soon after its installation. When the photovoltaic pump was installed at Weg, the diesel pump had already stopped operation for two years due to maintenance need. The PV system with its continuous operation for four years has amply demonstrated to the users in its reliability without incurring any repair and maintenance cost so far.The PV irrigation pumping system at Awash-Melkassa, when installed there were already two operational wind pumps on the site. These pumps had been operational on and off and the last two years they have stopped operation due to maintenance need and one of them has even been totally torn apart by the wind and the weather condition on the site. On the other hand, the PV pump has been running smoothly and efficiently without any repair. Maintenance and other running cost for the PV system has been uil since its installation and is highly accepted by the community.

To establish the viability of a phtovoltaic water pumping system either for irrigation or potable water supply system of rural communities, in addition to the acceptance of the system by the people, comparisons have to be made between a PV system vis-à-vis other water pumping technologies as well. The other water pumping technologies for rural application are the **hand, wind** and **diesel pump** systems.

Hand Pumps

Hand pumps are typically for a single or very few families usage. For communal use there must be more than a single system and this is only possible if the site permits The system is operable up to a depth of 50m and as the well gets deeper the discharge gets smaller. The system can be used in both hand dug or borewells. With its low discharge rate per day the system is seldom used for irrigation other than potable water supply. The total system can be acquired for less than USD 500.00. With the new hand pump systems, village level operation and maintenance (VLOM) has been made possible, but the failure rate of the pumps is still high.

Wind Pump System

Windmills have been in use for centuries and there are quite a variety of designs. Depending on the average wind speed available in the area which is dependent on altitude, height and location, the energy from the wind can be converted for grinding cereals, producing electricity or for pumping water. Average wind speeds between 3.5 to 5 m/s are sufficient for water pumping application.

Wind pumps can be used for either potable water supply from a borewell or for irrigation purposes from large bodies of water such as rivers or lakes. But as the pumping head increases the rate of water discharge decreases. System is operational up to 150m head and of course with reduced water discharge on high heads. Wind energy is seasonal and as such one cannot predict with all certainty on its availability on a range of days of a particular month. Its reliability is low and may give a problem if it is the only energy source available especially for water pumping. Its operating characteristic would also require a storage facility, thus adding the systems cost.

The systems cost has two components : initial investment or systems cost and repair and maintenance cost. The repair and maintenance of windmills needs trained personnel and there is a need for a stock of replacement parts.

Diesel Pumps

Diesel/gasoline pumps could be used at all heads with high discharge rate. The cost of the system, although disbursed over a long time, the running cost for fuel, spare parts, repair and maintenance are high. The need for skilled personnel to do the repair and maintenance job limits its usage for rural application, as witnessed by the breakdown of the diesel system at Weg that left the people without water for over two years.

COST COMPARISON FOR A DIESEL AND PV SYSTEM

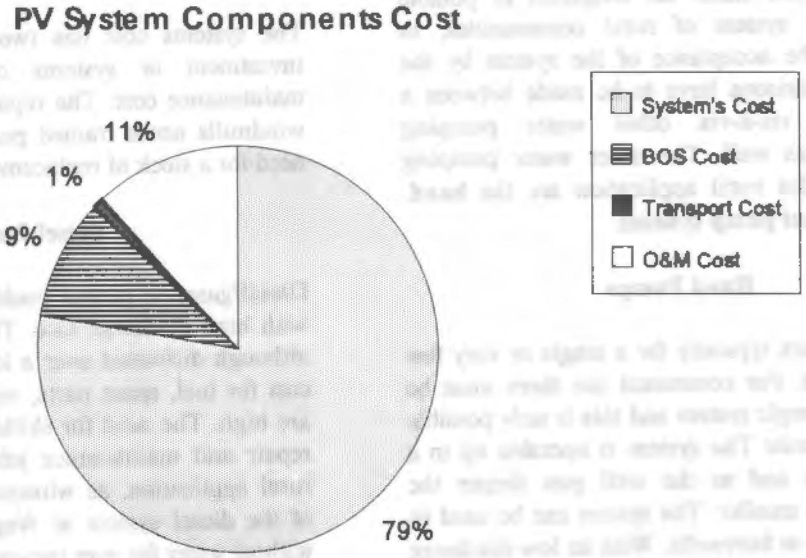
In comparing a diesel and phtovoltaic water pumping systems in addition to the systems initial investment cost one should also consider the infrastructure cost, storage need and operation and maintenance cost. The infrastructure cost for a PV system apart from a small masonry work for mounting the array and the fencing tp protect the system, the electronic components could be conveniently mounted outside in the shade of the modules. For a diesel system a small shelter to protect the unit from dust and rain is necessary. Comparing the infrastructure cost for both it could almost match. The storage facility needed for the pumped out water is the same for both. The cost difference comes out in the initial investment cost and the operation and maintenance cost.

The cost figures for the pumping equipment and auxiliaries being comparable and the energy conversion factors neglected, the present value of the life cycle (over a 20 year period) specific electricity cost for both systems have been compared under the following parameters:

Diesel System - 5KVA
- present value of fuel cost - Birr 0.27 per kwh
- fuel transport cost - Birr 0.035 per kwh for 100km distance
- operation and maintenance cost - Birr 0.125 per kwh
- Diesel engine unit cost - Birr 5000.00 per KVA
- inflation rate of diesel cost - 15%
- Diesel engine life time - 11 years
- real discount rate - 10%
- number of diesel replacements - 1
- maintenance inflation rate - 4%

Photovoltaic System - 1.6 kw_p
- cost of array - Birr 45.00/w_p
- Balance of System (BOS) cost - 12% of system's cost (includes cost of inverter, support and junctions)
- life time - 20 years
- maintenance cost - 0.5% of system's cost
- Average Insolation level - 5.4 $kwh/m^2/day$

The cost components as a percentage of the total systems cost for each is as shown in the graphs of Fig.5.



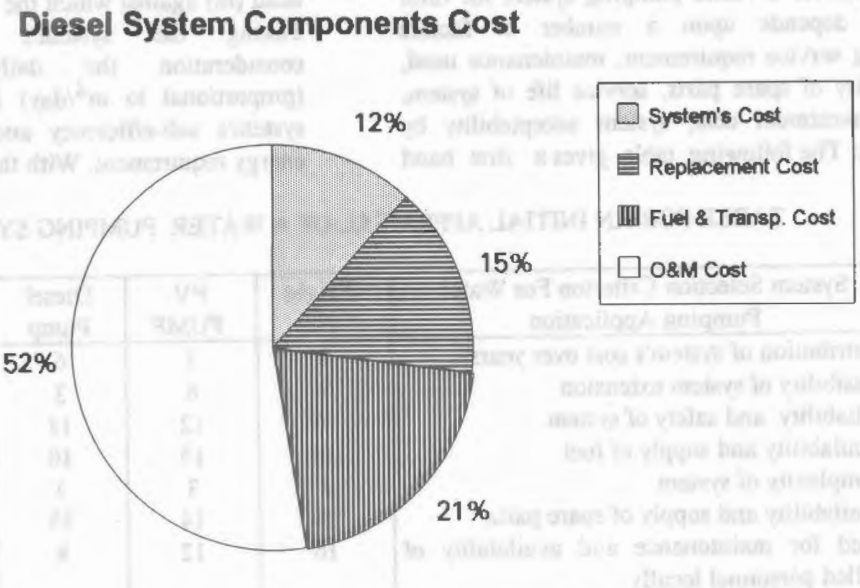


Figure 5 Cost Comparison for a 5kva Diesel and 1.6Kw_p Photovoltaic System

The energy cost as a function of the total energy that can be produced to pump 20 to 25 cu.m of water per day is as shown in Fig. 6. The unit energy cost for a 10 KVA diesel and 3.2 Kw_p is also included for comparison purposes.

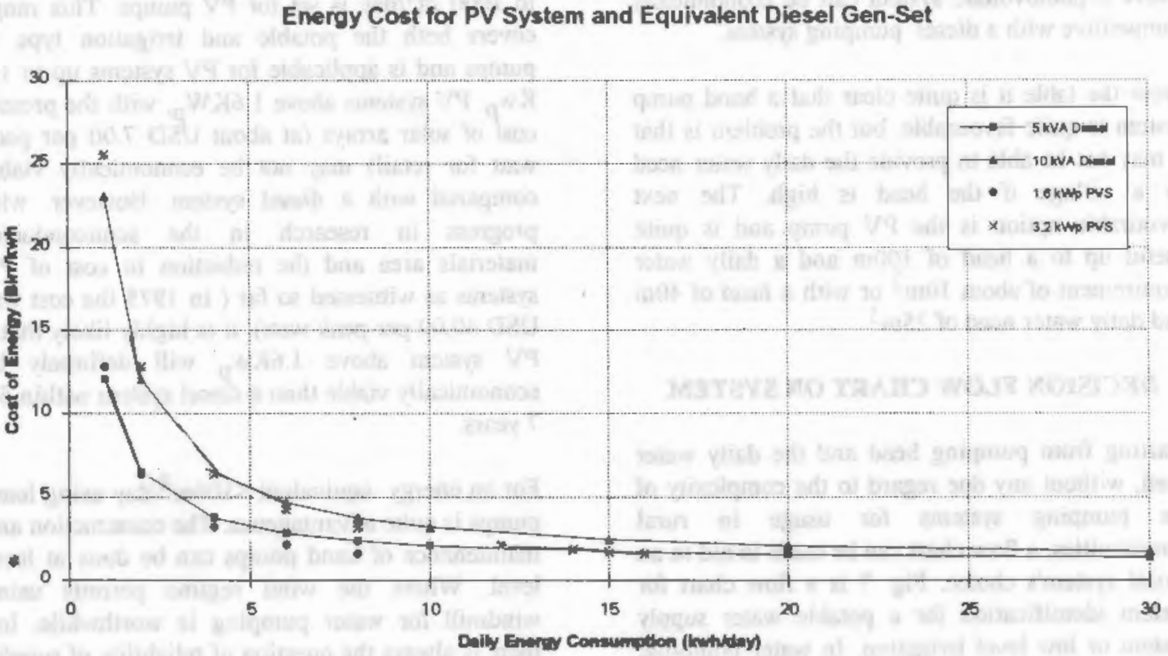


Figure 6 Energy Cost Comparison for Diesel and PV Systems

The choice for a viable pumping system for rural settings depends upon a number of factors including service requirement, maintenance need, availability of spare parts, service life of system, initial investment cost, system acceptability by users, etc. The following table gives a first hand appraisal for the different types of rural water pumping systems either for potable water supply (up to 25m^3/day) or for low level irrigation schemes (up to 150m^3/day). This range covers where a photovoltaic system can be economically competitive with a diesel pumping system.

TABLE FOR AN INITIAL APPRAISAL OF A WATER PUMPING SYSTEM

No	System Selection Criterion For Water Pumping Application	Weight (%)	PV PUMP	Diesel Pump	Wind Pump	Hand Pump
1	Distribution of system's cost over years	8	2	6	5	4
2	Possibility of system extension	7	6	3	3	3
3	Reliability and safety of system	16	12	12	9	12
4	Availability and supply of fuel	18	15	10	10	14
5	Complexity of system	4	3	2	3	3
6	Availability and supply of spare parts	16	14	10	14	15
7	Need for maintenance and availability of skilled personnel locally	16	12	8	14	15
8	Ease of transportation and installation of system	4	3	2	2	3
9	Ease of operation of system	6	5	3	3	5
10	Acceptance of system by community	5	4	3	3	4
	Total (%)	100	76	59	66	79

From the table it is quite clear that a hand pump system is quite favourable, but the problem is that it may not be able to provide the daily water need by a village if the head is high. The next favourable option is the PV pump and is quite useful up to a head of 100m and a daily water requirement of about 10m^3 or with a head of 40m and daily water need of 25m^3

DECISION FLOW CHART ON SYSTEM

Starting from pumping head and the daily water need, without any due regard to the complexity of the pumping systems for usage in rural communities, a flow chart can be made to aid in an initial system's choice. Fig. 7 is a flow chart for system identification for a potable water supply system or low level irrigation. In water pumping, the daily energy requirement is proportional to the product of the water need per day (m^3/day) and the head (m) against which the water is to be pumped. Taking the system's sub-efficiency into consideration the daily energy demand (proportional to m^4/day) is the product of the system's sub-efficiency and the daily hydraulic energy requirement. With the daily energy demand as an input one can go through the flow chart for making a quick and an initial appraisal of the system satisfying the conditions set. From the decision chart, an energy equivalent between 100 to 1000 m^4/day is set for PV pumps. This range covers both the potable and irrigation type of pumps and is applicable for PV systems up to 1.6 Kw_p. PV systems above 1.6KW_p, with the present cost of solar arrays (at about USD 7.00 per peak watt for retail) may not be economically viable compared with a diesel system. However, with progress in research in the semiconductor materials area and the reduction in cost of PV systems as witnessed so far (in 1975 the cost was USD 40.00 per peak watt), it is highly likely that a PV system above 1.6Kw_p will definitely be economically viable than a diesel system within 5 - 7 years.

For an energy equivalent <100m^4/day using hand pumps is quite advantageous. The construction and maintenance of hand pumps can be done at local level. Where the wind regime permits using windmill for water pumping is worthwhile, but there is always the question of reliability of supply. Here again, windmill can be constructed and maintained with local skill.

CONCLUSION

The need for commercial type of energy source is very high for both the urban and rural population of Ethiopia. With a high percentage of the population leaving in the rural areas with a predominantly agricultural economy, focus must be made on the energy supply that helps to develop the agricultural activities in the Country. For rural communities with neither short nor mid-term prospect for grid electricity connection, the photovoltaic system is a strong alternative in satisfying the energy demand especially for water pumping purposes.

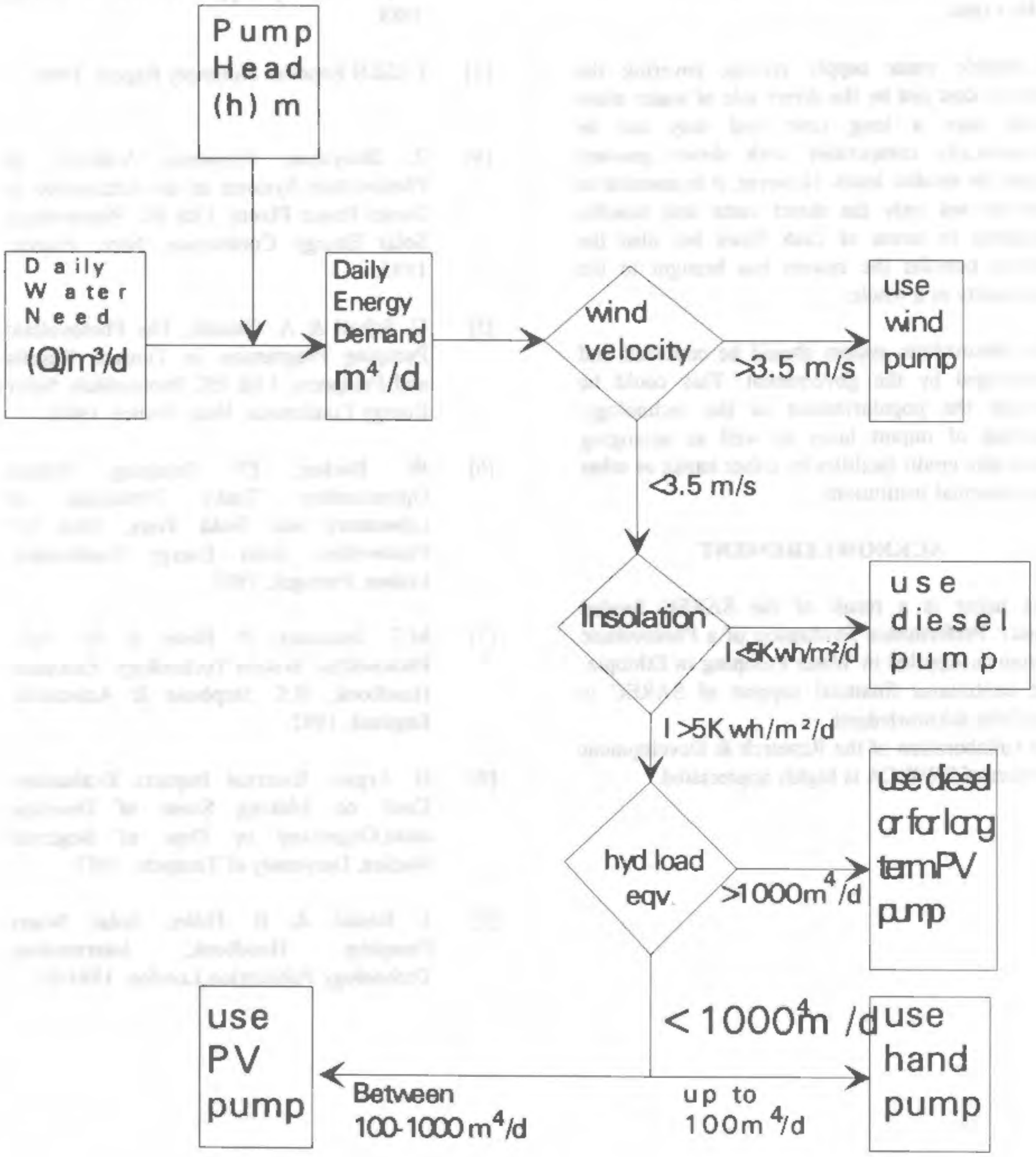


Figure 7 Decision Flow Chart for an Initial System Identification for Water Pumping

The high initial investment of the system should not necessarily be taken as a deterrent for its utilization. Every energy supply system does have its costs, risks and benefits and the photovoltaic system is no exception and one should also weigh its direct and indirect benefits. For irrigation purposes the system's cost coverage will be within a short time.

In potable water supply system, covering the system's cost just by the direct sale of water alone would take a long time and may not be economically competitive with diesel gen-sets except for smaller loads. However, it is essential to consider not only the direct costs and benefits measured in terms of cash flows but also the indirect benefits the system has brought to the community as a whole.

The photovoltaic system should be endorsed and encouraged by the government. This could be through the popularization of the technology, lowering of import taxes as well as arranging favourable credit facilities by either banks or other governmental institutions.

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