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Photovoltaic Water Pumping Systems in Rural Areas

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Abstract: In this paper, we propose a scientific and technical report, which gives briefly an over view on photovoltaic water pumping systems and provide some recent data on their actual situation and developments in the typical case of Morocco which is characterized as having high insulation and vast rural areas, with few villages connected to the national electricity grid.

Key words: Photovoltaic • Water • Pumping • Rural Areas • Morocco

INTRODUCTION

Providing a reliable water supply for both human consumption and agricultural needs in rural areas is one of the major problems facing North African Mediterranean countries. Typically water is extracted manually from deep wells located some way out of the village, occupying women and children for a large part of the working day. Furthermore, this method of water extraction cannot serve much needed irrigation requirements for agriculture in the region.

Photovoltaic conversion frequently offers the most cost-effective solution for powering water pumps using solar water pumping systems whish have many advantages. Indeed, they are reliable stand-alone systems that require no fuel and very little attention. Generally, when water is needed most, is when the sun shines the brightest. Solar panels generate maximum power in full sun conditions when larger quantities of water are typically needed. Because of this natural matching effect, solar water pumping is an obvious and economical choice over windmills and engine-driven generators for most locations away from utility power. However, many developing countries are still not yet gaining maximum benefit from this most important and useful photovoltaic application in remote areas for the following reasons: lack of awareness of the powerful usefulness of the technology, initial cost of plants, low reliability of installed systems, imperfect design of the system, scarce comprehension of the reasons why the plant fails and very low level of maintenance provided to the installed systems.

In this paper, we propose a scientific and technical report, which gives briefly an overview on photovoltaic water pumping systems and provide some recent data on their actual situation and developments in the typical case of Morocco which is characterized as having high insulation and vast rural areas, with few villages connected to the national electricity grid.

Overview on Photovoltaic Water Pumping Systems: Technical description of a standard photovoltaic pumping system: Photovoltaic water pumping systems in remote areas has proven a high technical reliability and economic feasibility over other traditional systems like diesel. Technically, these systems utilize the free solar energy to pump water from a well, a spring or any other source to an elevated reservoir from where the water is to be distributed to the consumers. The required electric power for these systems is produced by a solar generator that converts solar energy into electricity by photovoltaic conversion process. The solar generator is mainly consisting in photovoltaic panels in which solar cells are arranged in specific order (series and/or parallel) so as to provide the required values of DC current and voltage for the pumping system. The output power of this generator can directly drive a DC-Motor pump set, or can be converted into an AC power by means of a DC/AC inverter in order to drive a common AC-Motor pump. This inverter can be equipped with a maximum power point tracker in which operating current and voltage is selected to achieve maximum operational power. The motor pump set which is basically the third part of a photovoltaic pumping system is mostly installed inside the water.

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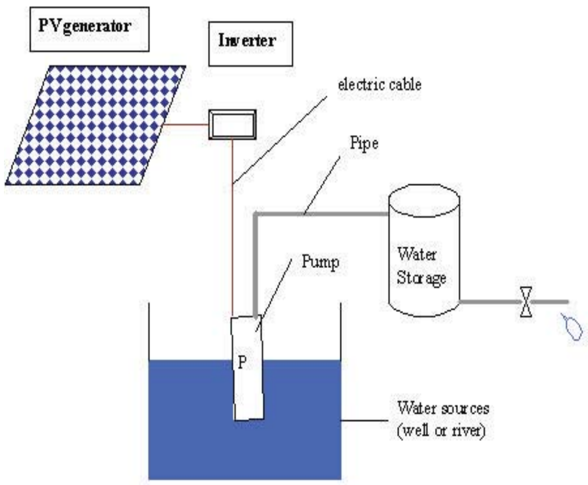

Fig. 1: Schematic Diagram of a standard photovoltaic water pumping system [1]

A three phase AC motor is nowadays the most common reliable type that can be operated without any maintenance requirements. In general it drives a submersible deep well pump, preferably made of non-corrosive stainless steel material.

In general, the standard photovoltaic water pumping system consists of the following main components as shown in Figure 1:

- Photovoltaic Solar Generator.
- DC/AC Inverter.
- Submersible motor pump set.
- Complementary components like storage tanks, pipes…etc.

The system does not include any batteries; instead the water tank is used for bridging the demand during night time hours and cloudy days.

Common Types of Pumps and Main System Characteristics: Different types of pumps have been tested and utilized for photovoltaic pumping applications. Many research projects have been sponsored to conclude the most efficient types of pumps. Main features of different systems have been extensively described in the literature [2]. Nowadays, the most popular of them is the three phase centrifugal submersible motor pump set which uses a multistage pump and a sine-wave inverter. The main advantages of this system are:

- Wide range of pumps are available for any well characteristics.
- Good adaptation of pump performance to solar radiation by means of high efficient DC/AC-inverter.
- Acceptable lifetime and high reliability of motor and pump.
- Very little wear and tear of moving parts.
- Standard components, same as used for grid-connected deep well-pumps known by users and service companies.
- Different manufacturers with different manufacturing materials are available.
- Good availability of spare parts.

Competing Water Lifting Devices: When planning to install any photovoltaic water pumping system to provide a service, all possibilities shall be considered. A comparison study shall be conducted and the most techno-economic system should be selected. In this regard, it is important to have an idea about the main characteristics of these systems considering the capacity in terms of Daily Hydraulic Energy (DHE) needed. Table 1 shows these characteristics. It is worth noting that DHE is calculated as follows:

DHE = Water discharge (Q) $*$ Pumping head (H)
= Q [m^3/day] $*$ H (m)
= Q $*$ H [m^4/ day] (Conversion factor: 1 kW = ~ 367 m^4/h)

Site Criteria for Photovoltaic Water Pumping Systems: One of the most important factors for photovoltaic water pumping application is the site criteria. The site should be suitable for applying this technology from all aspects. It directly affects the initial cost of the system required which is considered as the key element that affects the progress of this technology. As a first approach to photovoltaic water pumping system selection the following factors shall be evaluated:

- Water source with acceptable quality must be available and it should be not possible to provide this water for consumption without using energy.
- Techno-economic study should prove the advantages of this technology over other traditional alternatives like diesel system.
- Electric grid should be far away from the site and it shall be clear that it is not economic to extend it to the site.
- Pumping head (H) and flow rate (Q) should be within limited values (i.e. H $*$ Q < certain economic value of (m^4/day).
- This technology should be accepted by users.

Table 1: Main characteristics of competing water lifting devices

Pump type	Characteristics
Hand pump	Maximum pumping head ~ 45 m
	Maximum DHE (8 h operation) 200 m^4/day
	Efficiency 40% - 80%
	No need for storage tank
Diesel pump	Limited minimum size
	Field efficiency 4% - 15%
	Operation time responding to the demand (flexible)
	Low investment cost
	Intensive service and maintenance
	Pollution by fuel, lubricant, exhaust gases and noise
Photovoltaic pump	Daily overall efficiency 2.7% - 7%
	Operation time responds to weather conditions (need for storage tank)
	Low operating cost
	High investment cost
	Low specific water cost if constant daily demand
	and high irradiance without seasonal variance
	Reduce service and maintenance
	Pollution free and No noise

Table 2: Site criteria for the photovoltaic water pumping systems

System Site	Criteria
Positive Site criteria	- Other solutions are unavailable
	- Power demand is too high for hand pump (DHE > 200 m^4)
	- High costs or unreliable supply for diesel fuel (sites with little and dispersed population)
	- High solar irradiance without much seasonal variance
	- Steady water consumption over the year (irradiance matches water demand)
Negative site criteria	- Financial availability doubtful
	- Extension to electric grid feasible
	- Low fuel cost on site
	- Fluctuating water consumption (Cattle, irrigation)
	- Low irradiance and high seasonal variance
	- High power requirement (DHE is too high)
	- Drawdown of well is significant
	- Acceptance doubtful
	- Population is used to diesel pumps
	- Storage tank capacity is too small
	- Community has no experience in water management

Depending on the location and the economic situation of the site especially price level like fuel cost, the site criteria may have a positive or negative effect on the photovoltaic water pumping systems. These criteria should be taken into consideration for the site selection so as to make these systems technically, economically and socially successful. Table 2 shows these criteria.

Site Data for Photovoltaic Water Pumping Systems Design: Before making any serious decision for installing a photovoltaic water pumping system on a specific site, the exact site data should be prepared by technical staff or a consultant specialized in this kind of photovoltaic systems. Based on these data, the supplier or the designer can calculate the exact system requirements on which the system components are purchased and installed. After that, an acceptance test should be executed to ensure that the delivered components are matching the requirements or not. For that, the technical site data are very important in this regard.

The design procedure of the photovoltaic water pumping system depends on the data of the sites where theses pumping systems are to be installed. These data should be collected carefully to make a correct design and implementation of the system. The main advantage of a precise and complete data-basis is the better comparability of the received quotations, because the technical specifications clearly define the limits of the offered equipment. The required data are detailed elsewhere [2]; they mainly include the characteristics of water source, the water requirement in term of demand/consumption and the meteorological information.

Finally, after accumulating all necessary data, the supplier can now calculate and design the photovoltaic water pumping system, according to the data submitted by the customer. As more detailed the data submitted by the customer are, as less assumption have to be made by the supplier and as more precisely the offered system will fit to the real circumstances on site. Even if the supplier shall not deliver certain components (e.g. pipeline, cable, water meter, wellhead etc.), he/she might give some recommendations for minimum requirements like cross-section, cable dimensioning, etc.

Applications: Photovoltaic water pumping systems have proved a high reliability in different fields of applications where electricity network is not available. There are several successful possibilities of application especially in remote areas. They include village drinking water supply, drinking water supply for livestock and small-scale irrigation. Indeed, the problem of ensuring a steady supply of drinkable water remains unsolved in many countries. Pumping systems can be used to obtain pure ground water from deep wells instead of surface water that is frequently impure and biologically contaminated. Pure well water is also a basic need for animal herds. A reliable and continuous supply of drinking water can make the raising of livestock possible and noticeably increase the size of existing herds. Furthermore, as population grows in the countries, the carefully directed irrigation measures can serve to intensify food production.

Actual Situation of PV Water Pumping in Morocco: In this second part of the paper, we provide some recent data on the actual situation and developments of photovoltaic water pumping systems in the typical case of Morocco which is characterized by high insulation and vast rural areas, with few villages connected to the national electricity grid.

Water Supply in Moroccan Rural Areas: The rural population in Morocco includes 13,428 million inhabitants living in 32,000 douars [3]. The population per douar ranges between 250 and 1000 people, with an average of 420. There are also 1500 rural centres with a population of 3 million people and an average of 1,980 people per centre. The access to water in rural areas is not even and depends on the regions, the provinces and the municipalities. Overall, it is calculated that 61% of people have access to drinking water in rural areas, representing 8.2 million people living in 16,550 rural settlements.

A programme for water supply for rural areas (PAGER) [4] was established in 1995 with the objective to supply drinking water to 31,000 rural settlements and 11 million people, with an overall investment of 11 million dirham. The Moroccan General Directorate of Hydraulics was responsible for the distribution systems to provide water to 27,000 settlements and ONEP (Office National de l'Eau Potable) was responsible for the regional infrastructure to provide water to 4,000 settlements.

Initially, the objectives of PAGER included: a) the provision of drinking water to 11 million people living in 31,000 settlements with an investment of 10 million dirham; b) increase of water supply from 14% in 1994 in rural areas to 80% in 2010. By the end of 2004, however, the objectives were re-evaluated. The targets were to supply drinking water to 8.2 million people living in 16,500 settlements and increase the water supply from 14% in 1994 to 61% by the end of 2004.

The water projects developed under PAGER required the participation of the populations from the planning to the implementation of the projects. It is important to note that the populations in the different rural settlements have been responsible for covering part of the initial subsidised expenses for the pump and the meter, as well as for its maintenance. Members of the Third World Centre for Water Management visited some rural settlements in the area of Sidi Kacem in 2002-2003. In the settlements visited, people had paid (some times not without initial disagreements) the initial agreed cost of the pump and were covering its maintenance. One family was responsible for selling the water to the villagers who were willing to buy it. This family would be given the water at a certain price and they would charge a smaller amount more in order to cover the maintenance costs. At the end of the month, the institution responsible would come to the settlement and would be paid by the water used. The family kept the pump scrupulously clean and the meter had not been broken. It was clear by the reactions and discussions of the nearby population that the demand for pumps in the individual settlements was higher than what could be provided.

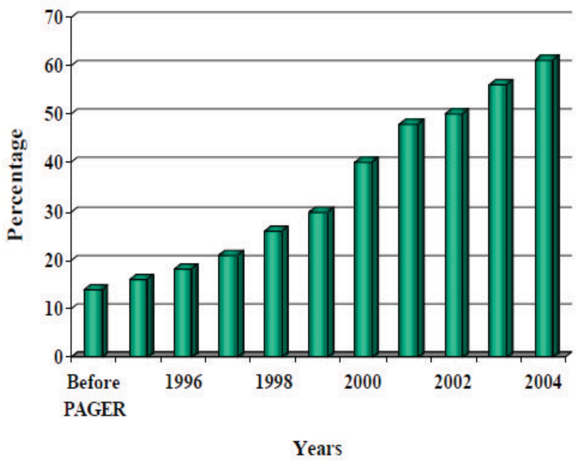

Fig. 2: Water supply service to rural settlements under PAGER during 1994-2004 period.

Figure 2 shows the improvements of drinking water supply service during 1995 - 2004 period under PAGER. As it can be observed, the access to drinking water has increased from 14% before PAGER, to 16% in 1995 and to 61% in 2004. The number of settlement with water supply has also increased, from less than 3,000 in 1995 to almost 8,000 in 2000 and more than 16,000 in 2004.

During the 1995 - 2001 period, eight small settlements with 22,000 people were supplied with drinking water. However, only during 2002 - 2004, the service increased to 30 small settlements and 80,000 people were served per year.

In 2001, during the 9th session of the High Council for Water and Climate, a series of reforms for the water sector were put in place. According to these reforms, ONEP would be responsible to supply drinking water to the rural areas in the country from January 2004. The objective was then to reach coverage of 90% of the rural settlements by 2007.

Regarding the infrastructure for drinking water supply for rural areas, ONEP considers that more than 70% of the rural population can receive drinking water with the already existing infrastructure. These includes 5,500 pumps, 2320 sources of water, 26,000 km of pipes, 8,000 reservoirs, etc.

The private sector is involved in two pilot projects which provide drinking water to rural areas. One of them includes the supply of water to 17 douars and the other one, the use of photovoltaic water pumps for about 10 rural settlements in the south.

Lessons from Photovoltaic Pumping Programmes in Morocco: In the framework of Moroccan photovoltaic water pumping programmes achieved to supply water for rural communities, several lessons have been learnt in the design, installation, operation and maintenance of systems used. The experience shows a picture of the state of the art, related to centralized photovoltaic water pumping systems with a distribution network. The pumps have been tested in a laboratory and despite the best efficiency expected at nominal power rates, the high start threshold could be a problem which causes decreasing of daily flow rate [5].

Summary of Systems: The experience started in 1996, with the installation of 10 isophoton pumping systems (22.6 kWp supplying water to 8500 inhabitants) in villages of the Draa Valley, in the south of Morocco. The success obtained from the technical point of view, as well as from the socioeconomic impact, allowed the enlargement of the systems installed in other project, up to the installation of 12 systems more (24.1 kWp for 11500 inhabitants), under the promotion of Fundación Iberoamérica Europa (CIPIE) and financed by the European Commission and the Agencia Española de Cooperación Internacional (AECI). In the Framework of the European Commission Program MEDAS, other 49 pumping systems comprising 137 kWp are currently being installed in Morocco, together with 13 systems in Tunisia (59 kWp) and 10 systems in Algeria (59 kWp).

Power Conditioning Equipment: Developed during 8 years, the power conditioning equipment installed have evolved from the initial use of special solar inverters designed for specific photovoltaic applications and using special solar pumps, to standard variable frequency inverters feeding standard AC three phase pumps, with the advantage of availability of wide traditional market for inverters and pumps, enlarging the capability of the systems and optimizing the photovoltaic system performance. Also the hydraulic design has evolved, in order to achieve high reliability. The systems include the distribution network to the dwellings and photovoltaic chlorination devices have been installed, to improve water quality.

Specific photovoltaic pumping sets (inverter + pump) got useless due to their limited power and the small available product line; under these conditions variable frequency drives plus standard three phases pump give a solution to the problem.

Standard AC pump optimized for every flow rate/mano-metric head needs is available in the market. Why should we turn to use down this benefit? A new problem appears, how could we supply these (usually three phases) pumps?

The answer is in the Variable Frequency Drives (VFD). They can be fed directly in DC and with the corresponding hardware and software adaptations supply an AC voltage/frequency proportional to the solar irradiance and a flow rate as a function of this variable voltage/frequency. With these two elements we do not have any power limitation to size a photovoltaic pumping system.

The first generation of Isophoton direct photovoltaic pumping systems using VFD included an external electronic control board that made the PV array work around a prefixed point in their I/V curve and near to their Maximum Power Point. This board adds to a very robust system an element with low reliability becoming the weakest component in it (in fact it was the element more often replaced in some of the Draa Valley Project systems)

To solve these occasional problems, the second generation of Isofoton direct photovoltaic pumping systems using PID speed controllers was developed. In these systems the control board is replaced with the adequate settings on the PID parameters together with slight hardware modifications, being in this moment the technology used.

Systems are continuously growing and protection against dry running of the pump was necessary. The initial three wires (submerged in three different depths in the well) electronic gauge was replaced with an electronic control of the pump speed, that avoids the problems due to the different water salinity (wrong system stops) and the need of a periodical substitution of the three sensing wires caused their corrosion.

Simulation Program: A program of simulation has been developed for pumping systems with frequency converters, using the scientific software package for numerical computation Scilab (www.scilab.org). The simulation uses as initial information:

- H-Q Curves of the SP range of the Grundfos manufacturer. These curves use the experimental measurements taken in the IER laboratory of the CIEMAT, Madrid [6, 7].
- Hydraulic efficiency curves of the SP pump.
- Electromechanical efficiency curves of the SP motor-pump engine.
- Total dynamic head (including friction losses). It remains constant during the simulation.
- Daily minimum stream flow.
- Radiation level and standard on of the place, according to IEC 61725 [8].
- Environmental Temperature, which remains constant during the simulation.

The process of simulation consists of two phases, Firstly there is a simulation of the complete system from a frequencies vector (range that sweeps the frequency converter adapted to the concerning pump). That is to say, we start with the useful inflow to finish with the power delivered by the generator.

This simulation uses the H-Q curves across the typical equation typical of the pump (a, b and c are pump parameters):

$$H = a \cdot f^2 + b \cdot f \cdot Q + c \,.Q^2 \qquad (1)$$

This equation based on the similitude criteria that holds any centrifugal pump (P = hydraulic power) incorporates the effect of the frequency variation. Therefore, derived from the vector frequency vector the is obtained the instantaneous flow rate vector (assuming total dynamic head). Again with the similitude criteria, there is obtained the maximum hydraulic spectral power value associated with every frequency and therefore, a hydraulic power vector.

Later, the necessary power input to the pump is calculated (mechanical power given by the engine). This operation uses the efficiency curve of the pump. It must be taken into account that this curve provides values for a frequency of 50 Hz and it is necessary to resort to the similitude criteria to realize the calculation for every value of the frequencies vector.

With this vector of mechanical power it is possible to calculate the electrical output vector (power input to the engine) by means of the engine efficiency curve.

$$\frac{f_1}{f_2} = \frac{Q_1}{Q_2} = \left(\frac{P_1}{P_2}\right)^{1/3} = \left(\frac{H_1}{H_2}\right)^{1/2} \qquad (2)$$

Once more, this curve is distinguished at the frequency response of 50 Hz. Nevertheless, the engine does not comply with similitude criteria. To realize the conversion one can use a linear phase relationship [9]:

$$P_{bc} = P_b \cdot \frac{50}{f} \qquad (3)$$

Finally, there are calculated the electrical power input vectors of the frequency converter and the output of the photovoltaic generator assuming constant values in the converter efficiency and the general cabling system.

With this group of vectors it would start the second phase of the simulation. Now, we will begin in the generator to end in the delivered flow. Then we use the standard local radiation, either by of hourly values, every minute, etc. These values of radiation allow to calculate the instantaneous power provided by any photovoltaic generator of rated power (later is indicated how to calculate the first value in this iteration).

We obtain, therefore, a DC power vector from the radiation vector. Linking the values of these vectors to the obtained ones in the phase 1 (that distinguished each of the conversion stages) so that the supplied power in every step is superior to the demand set up in the phase 1, we will be able to relate the radiation vector to the flow rate vector. This relation allows to calculate for integration the daily flow produced by a photovoltaic generator connected to a certain pump that surpasses the constant total dynamic head.

The maximum power value of photovoltaic generator is obtained after an iterative process taking the provided daily flow as a target. As first value of this iteration one can use the equation (2):

$$P^*(W) = 10 \cdot \frac{G^*}{G_d} \cdot Q_d(m^3) \cdot H_{TE}(m) \qquad (4)$$

Being P* the nominal power of the generator, G_d the daily annual average irradiation, G* the value 1000 W/m^2, Q_d the daily flow, H_{TE} the total dynamic head.

RESULTS

Figure 2 submits the comparison of the flow rate foreseen and obtained in the Morocco Project, which has operated by the larger period. Real data shows good mismatch with the expected values.

Reported performance of the systems shows a successful reliability, with very low percentages of failures, only in inverters and press switches.

It will be remarked that one of the main aspects for the project success has been the participation of local players, like the NGO Tichka, which deals with the social organization, traduced in a high participation of users during installation and operation and in the creation of local associations, devoted to managing the systems, in the economics aspects, collecting monthly fees devoted to devices replacement, as well as training the users for optimal operation and maintenance of the systems.

As a result of the simulation method employed, a family of charts had been created, allowing an easy previous dimension of photovoltaic pumping system. An example of such charts are submitted in Figure 3.

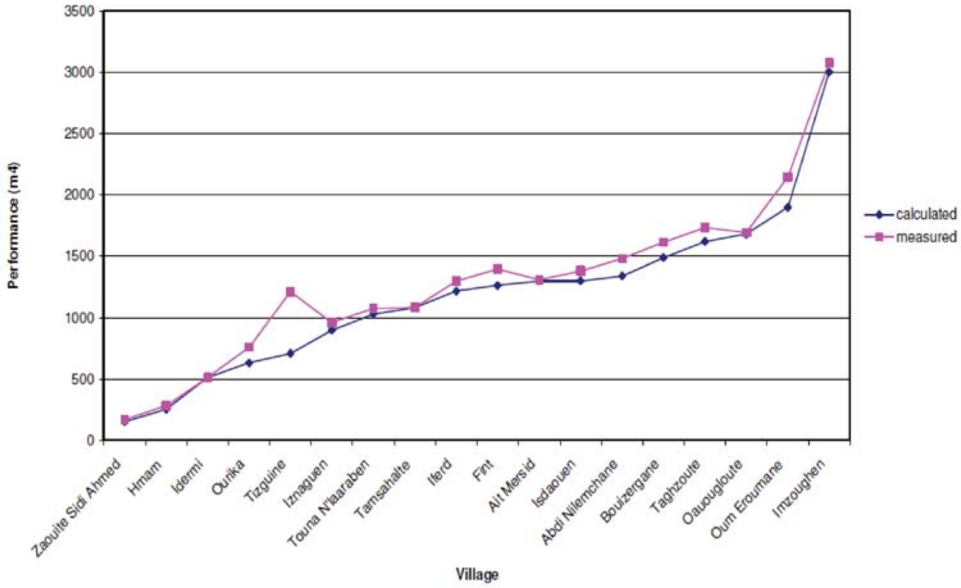

Fig. 3: Measured and calculated pumping performance for the different village considered

CONCLUSIONS

Lessons learned during the described projects allow to conclude that the use of frequency converters feeding standard AC submersible pumps is reliable, cost successful and efficient. In despite of the complexity of programming such devices, which have the same pattern of quickly evolution of the models available, characteristic of electronic equipments of last generation, the results obtained recommend their use, even when more often training is required for technicians and installers.

As in all rural projects, the social aspects related with the introduction of new technologies and the active participation of the end users of the systems, are the key point for the project success.

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