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Abstract: The exploitation of solar energy in remote areas through photovoltaic (PV) systems is an attractive solution for water pumping for irrigation systems. The design of a photovoltaic water pumping system (PVWPS) strictly depends on the estimation of the crop water requirements and land use since the water demand varies during the watering season and the solar irradiation changes time by time. It is of significance to conduct dynamic simulations in order to achieve the successful and optimal design. The aim of this paper is to develop a dynamic modeling tool for the design of a of photovoltaic water pumping system by combining the models of the water demand, the solar PV power and the pumping system, which can be used to validate the design procedure in terms of matching between water demand and water supply. Both alternate current (AC) and direct current (DC) pumps and both fixed and two-axis tracking PV array were analyzed. The tool has been applied in a case study. Results show that it has the ability to do rapid design and optimization of PV water pumping system by reducing the power peak and selecting the proper devices from both technical and economic viewpoints. Among the different alternatives considered in this study, the AC fixed system represented the best cost effective solution.

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Highlights

1. Evaluation of water demand and solar energy is essential for PV pumping system.
2. The design for a PV water pumping system has been optimized based on dynamic simulations
3. It is important to conduct dynamic simulations to check the matching between water demand and water supply.
4. AC pump driven by the fixed PV array is the most cost-effective solution.

DYNAMIC MODELING OF A PV PUMPING SYSTEM WITH SPECIAL CONSIDERATION ON WATER DEMAND

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ABSTRACT

The exploitation of solar energy in remote areas through photovoltaic (PV) systems is an attractive solution for water pumping for irrigation systems. The design of a photovoltaic water pumping system (PVWPS) strictly depends on the estimation of the crop water requirements and land use since the water demand varies during the watering season and the solar irradiation changes time by time. It is of significance to conduct dynamic simulations in order to achieve the successful and optimal design. The aim of this paper is to develop a dynamic modeling tool for the design of a of photovoltaic water pumping system by combining the models of the water demand, the solar PV power and the pumping system, which can be used to validate the design procedure in terms of matching between water demand and water supply. Both alternate current (AC) and direct current (DC) pumps and both fixed and two-axis tracking PV array were analyzed. The tool has been applied in a case study. Results show that it has the ability to do rapid design and optimization of PV water pumping system by reducing the power peak and selecting the proper devices from both technical and economic viewpoints. Among the different alternatives considered in this study, the AC fixed system represented the best cost effective solution.

Keywords: renewable energy resources, solar energy, photovoltaic system, pumping system, water demand.

NOMENCLATURE

Abbreviation

AC	Alternate current
DC	Direct current
ICC	Initial investment cost
MPPT	Maximum power point tracker
PV	Photovoltaic
PVWPS	Photovoltaic water pumping system
SCS	Soil conservation service

Symbols

e_a	Actual vapour pressure [kPa]
E_h	Hydraulic energy [kWh/day]
e_s	Saturation vapour pressure [kPa]
ET_0	Reference evapotranspiration [mm/day]
ET_c	Evapotranspiration in cultural conditions [mm/day]
EX	Extraterrestrial radiation (kWh/m2)
g	Gravity acceleration [m/s^2]
G	Soil heat flux density [MJ/m^2day]
GH	Global horizontal radiation (kWh/m^2)
H	Total dynamic head [m]
I_b	Beam radiation [Wh/m^2]
I_d	Diffuse radiation [Wh/m^2]
I_{tot}	Global radiation on the array [Wh/m^2]
$I_{tot,d}$	Daily total radiation [$kWh/m^2/day$]
$K_b(\theta)$	Incidence angle modifier
K_c	Cultural coefficient
K_d	Incidence modifier for diffuse radiation
LI	Longwave incoming radiation (kWh/m^2)
LO	Longwave outgoing radiation (kWh/m^2)
NOCT	Nominal operating cell temperature [°C]
P	Precipitation (mm)
$P(T,\theta)$	Power output [W]
Q	Water flow [l/s]
RH	Relative humidity (%)

R_n	Net radiation at crop surface [MJ/m^{2}day]
T	Temperature [°C]
T_a	Ambient temperature [°C]
T_c	Cell temperature [°C]
T_r	Reference temperature [°C]
u_2	Wind speed at 2 m height [m/s]
W_g	Water gross volume [mm/day]
WS	Wind speed (m/s)
W_t	Watered height [mm]
α	Power temperature coefficient [%/°C]
γ	Psychrometric constant [kPa/°C]
Δ	Slope vapour pressure curve [kPa/°C]
η_{0b}	Optical efficiency for beam radiation [%]
η_s	System efficiency [%]
η_p	Pump efficiency [%]
$\eta_{PV,T}$	PV module thermal efficiency [%]
η_w	Electric wires efficiency [%]
Θ	Angle of incidence [°]
ρ	Water density [kg/m^3]

1. INTRODUCTION

The availability of electricity in remote areas is one of the main issues regarding the design and operation of irrigation systems. Nevertheless, it is quite common in the developing countries that the access to the electric grid is unavailable. With the development of photovoltaic (PV) technology that can convert the solar energy to electricity, using PV cells has become a more attractive solution to provide the required power for the water pumping system, especially in the areas that have abundant solar energy resources [1]. The high technical reliability of PVWPSs for irrigation purposes, their long term economic viability and recent developments as well as the weaknesses have been shown by several studies and field experiences. The knowledge and the competencies achieved in this field resulted as starting point and recommendations for further and future programmes worldwide [2, 3]. For example, in 2009 the Government of Bangladesh has set as target for 2014 to install more than 10000 PVWPS for irrigation with a total installed capacity of 10 MW$_p$. Only in 2010 India has installed more than 50 MW$_p$ PV off-grid systems of which pumping system represent a large part [4].

Many studies have been carried out in the development of the PVWPS focusing on the system sizing, system modeling, economic performance and environmental feasibility. Models have been presented for the estimation of water demand [5, 6], assessment of the solar energy [7, 8], PV generator and controller [8, 9] and for the motor-pump system [10]. Some demonstration projects that link the power output from the photovoltaic generator, pumping system power consumption and instantaneous water flow output have been conducted [11]. Based on the available models, the approaches regarding the system optimization have been developed [12]. In addition, economic and environmental evaluations showed the feasibility of photovoltaic pumping system compared to traditional systems driven by diesel engines [13].

The main R&D gaps for the implementation of the PVWPSs exist not only in the technologies of PV and pump. Problems related to the local peculiarity need to be considered [14]. The local peculiarity includes water resources availability, water demand, different pumping system configurations, acceptance and management of the system. These issues need to be investigated in order to achieve the success of a photovoltaic pumping project. In addition, in the current state of the art the capital cost of a PVWPS is still higher than the traditional system driven by diesel engine, which is considered as the major barrier for the large scale commercialization, although the operation costs are much lower. Therefore, as regards the optimization, efforts are mainly focused on minimizing the cost.

Dynamic operation is one of the most important characteristics of the PVWP systems. Due to the dynamic variation of solar irradiation and the precipitation, the PV power output and the water demand of irrigation vary time by time. Meanwhile, as the solar irradiation varies, the dynamic PV power output would affect the performance of pump, resulting in a dynamic variation of pump efficiency and power consumption. In order to achieve the successful and optimal design and minimize the costs, the system dynamic characteristic has to be considered. The impacts of the dynamic variation of solar irradiation on the dynamic variation of water demand and pump performance have been investigated thoroughly. The objective of this paper is to develop a dynamic simulation tool and conduct dynamic simulations for a PVWP system, by integrating all of the dynamic variations of water demand, solar irradiation, PV power output and pump performances. Both AC and DC pump and both fixed and two-axis sun tracking systems were investigated from a technical and economic viewpoint. A dynamic water demand model was developed based on the local climatic conditions, soil characteristics and type of crops. With the predicted dynamic water demand the instant performances of PVWP system were studied. Such a dynamic simulation can be used to evaluate the existing design, checking if there is mismatch between the pumped water and the demanded water. The results would also give some guidelines or suggestion concerning system optimization from the perspective of dynamic water demand.

2. DESCRIPTION OF THE SYSTEM

A PVWPS is basically composed of a PV array, a power controlling system and a pumping system connected to the distribution system that can be a water tank or directly an irrigation system. A schematic diagram of the photovoltaic water pumping system studied in this work and the related models adopted is presented in Figure 1. The photovoltaic array consists of photovoltaic modules that are connected in series or in parallel depending on the voltage and current output requirements. In this work both fixed and two-axis sun tracking systems were investigated and compared technically and economically. The power controlling system is an interface between the PV modules and the motor-pump system with the function to improve the coupling performances. The power conditioning system can be a DC/DC converter or a DC/AC inverter depending on the motor-pump technology. Both converter and inverter are usually equipped with a maximum power point tracker (MPPT) device in order to maximize the power extraction from the solar array. In this study, both multistage centrifugal DC and AC pump and the related power controllers were adopted in order to investigate and compare the performances, especially in terms of power consumption, water pumped and costs.

Figure 1: Schematic diagram of a photovoltaic water pumping system.

3. METHODOLOGY

This study is divided into three parts: the estimation of the water demand for irrigation, the assessment of the exploitable solar energy and related power output from the PV array, and sizing and dynamic modeling of the system. The assessment of water demand depends on a lot of factors such as the type of crop, type of soil, irrigated area, rainfall regime, average temperatures, wind speed and solar radiation. Here the FAO Penman-Monteith method was used to estimate the water demand for growing Alfalfa (*Medicago Sativa*) in a sandy soil with some assumptions regarding the soil characteristics [5]. Based on this model both the assessment of the monthly water demand that is the input data for the design procedure, and the hourly water demand used in the dynamic modeling can be obtained. The assessment of the solar energy available and power output from the solar array was made on the basis of data provided by a global climatic database and processed by the program WINSUN considering different tilt angles and system configurations [7, 8]. The design process was carried out through the estimation of the water demand and hydraulic head for growing Alfalfa in order to estimate the power of the pumping system. The PV array power peak was then calculated on the basis of the daily required hydraulic energy, daily collectable solar energy and system efficiency. The worst conditions in terms of available solar energy and required water demand were chosen for the design procedure. The dynamic modeling of the photovoltaic water pumping system was used to prove and optimize the sizing process, underlining the match between water demand and water supply. A describing flow chart of the designing process and dynamic simulations carried out in this paper and the related parameters affecting both processes are presented in Figure 2.

Figure 2: Designing and dynamic modeling procedure.

The dynamic simulations were done based on the hourly data of solar radiation, angle of incidence and temperature in order to estimate the hourly power output from the PV array. The PV power output was then used to estimate the hourly water output of the pumping system according to the power input-instantaneous flow characteristic curve of the chosen pumps and power controller efficiency. The match between water supply and water demand was analyzed using the results achieved by the hourly dynamic modeling of water pumped and estimated water requirements on monthly basis. The economic analysis carried out in this work was mainly focused on the differences in initial capital costs between system equipped with AC and DC pump, fixed PV array and sun tracking array. The economic investigation was based on the prices referring to the Chinese market and taken from an on-line business-to-business trading platform [15].

3.1 Climatic data

The site chosen for this study was in Xining, the capital city of Qinghai Province, China, located on the eastern edge of the Qinghai-Tibet Plateau (Latitude: 36°37' N; Longitude: 101°46' E; Altitude: 2275 m a.s.l.). This location is featured by a continental cold semi-arid climate with high potential in solar energy. The monthly daily average temperatures range from -6.0°C in January up to 22.2°C in July. The annual precipitation is 269 mm and is mainly distributed between May and September. The annual global radiation on horizontal plane is 1542 kWh/m^2 with 2701 sunshine hours. The climatic data referring to Xining were taken from the global database provided by Meteonorm including temperature, relative humidity, precipitation, wind speed, global radiation on a horizontal plane, extraterrestrial radiation, incoming and outgoing longwave radiation as given in Table 1 [7]. The monthly statistical data were used for the estimation of the monthly average daily water demand and the sizing of the PVWPS. Whereas the hourly data elaborated by the software applying stochastic method were used for the dynamic modeling of the water requirements and the photovoltaic pumping system.

Table 1: Climatic data for Xining.

3.2 Water demand

The model adopted for the estimation of the water demand was based on assumptions regarding the crop and soil characteristics. In this study Alfalfa was chosen as growing crop whereas the characteristics of the ground referred to a sandy soil. Both characteristic parameters of the growing crop and soil used in this model and equations for the assessment of both average daily water requirements were taken from guidelines provided by FAO [5]. The reference evapotranspiration was estimated through the method FAO Penman-Monteith that is a procedure based on the climatic data of the site chosen for the irrigation system.

The daily trend of the reference evapotranspiration ET_0 was calculated taking into account the monthly average daily climatic data regarding solar radiation, temperature, humidity, vapor pressure and wind speed through the following equation:

$$ET_0 = \frac{0.408\,\Delta\,(R_n - G) + \gamma \dfrac{900}{T + 273}\, u_2\,(e_s - e_a)}{\Delta + \gamma\,(1 + 0.34\,u_2)} \qquad (1)$$

Where, Δ is the slope of the vapour pressure curve, R_n is the daily net radiation at the crop surface, G is the soil heat flux density, γ is the psychrometric constant, e_s is the saturation vapor pressure, e_a is the average daily actual vapor pressure and u_2 is the average monthly daily wind speed. The net radiation can be estimated as difference between the incoming net shortwave radiation and the net outgoing longwave radiation. Based on the hourly data of the involved parameters, the hourly water demand can be calculated from Equation 1 adjusted for one hour time step.

The evapotranspiration in standard cultural conditions, ET_c, was estimated from the reference value on the basis of the growing crop, climatic conditions, and soil characteristic parameters and the vegetative phase. These previous considerations are summed up in the cultural coefficient K_c. Then, ET_c is given by:

$$ET_c = K_c ET_0 \tag{2}$$

In the specific case of Alfalfa K_c varies from 0.4 to 0.95 depending on the growing phase of the crop: K_c equal to 0.4 in development phase, 0.95 during the intermediate phase and 0.9 in the final phase. The development phase runs from the sowing to the effective full ground cover, the intermediate stage from the effective full cover up to the crop ageing and the final stage from the ageing up to the harvesting. In order to size the system, in this study K_c was assumed equal to 0.95. The daily gross water volume needed by the crop W_g in mm/day can be estimated taking into account evapotranspiration in the standard cultural conditions, effective rainfall, potential application efficiency (*PAE*) and leaching requirement (*LR*). The gross water volume in mm/day is given by the following equation:

$$W_g = \frac{ET_c - P_e}{(1 - LR)\left(\frac{PAE}{100}\right)} \tag{3}$$

where P_e is the effective rainfall, which was estimated from the monthly precipitation data by applying the Soil Conservation Service (SCS) method developed by the United States Department of Agriculture [16]. In this equation, *LR* implies the amount of water needed in order to remove residual salts from the root zone whereas *PAE* refers to the efficiency of the irrigation plant. *LR* and *PAE* were set equal to 0.18 and 0.8 correspondingly, when assuming to use a micro irrigation system.

Another important parameter for PVWPS is the irrigation turn that permits the planning of the irrigation. The irrigation turn was estimated as the ratio between the amount of water released during an irrigation turn, W_t, and the daily gross water volume. W_t represents the maximum water volume that the crop can absorb without water losses. It depends on the water fraction absorbed by the crop, the wet surface due to the irrigation system, the roots depth and the soil water content [17].

The sizing of the system was based on the monthly average daily water demand, whereas the dynamic modeling was based on hourly values. The estimated hourly water demand was then compared with the hourly water supplied by the PV pumping system. Comparisons between water demand and water supply were made also considering a time step equal to the irrigation turn and on monthly basis for the whole season.

3.3 Photovoltaic array

The power output provided by the PV array varies especially due to the different conditions of solar radiation and temperature. Indeed those previous parameters affect the characteristic curve of the PV modules. The dynamic modeling of the PV system considered the estimation of the hourly power output of the solar array *P(T,ϑ)*, depending on the hourly beam radiation I_b and diffuse radiation I_d, incidence angle ϑ and temperature T. The following equation was used to evaluate the hourly power output from 1 kW_p PV array [18]:

$$P(T,\theta) = [\eta_{0b} K_b(\theta) I_b + \eta_{0b} K_d I_d][1 + (T_c - T_r)\alpha] \qquad (4)$$

Where η_{0b} is the optical efficiency for the beam radiation, $K_b(\vartheta)$ is the incidence angle modifier, K_d is the incidence modifier for diffuse radiation T_c is the cell temperature, T_r is the reference temperature (25°C) and α is the power temperature coefficient. The first term of Equation 4 represents the power output from 1 kW_p PV modules at the reference temperature, whilst the second term accounts for the power losses due to temperature deviation from the reference value. The influence of the temperature on the PV modules performance was taken into account through the cell temperature *Tc* that is affected by the ambient temperature T_a and the global solar radiation I_{tot} trough the following equation:

$$\mathrm{T_c} = \mathrm{T_a} + \left[\frac{(\mathrm{NOCT} - 20)}{800}\right]\mathrm{I_{tot}} \qquad (5)$$

Where, *NOCT* is the nominal operating cell temperature. Simulations of the power output from the PV array were conducted with WINSUN that is software based on TRNSYS system simulation [9]. The dynamic modeling of the solar array power output was estimated taking into account the hourly values of beam radiation, diffuse radiation, incidence angle and ambient temperature. The calculations carried out with WINSUN considered the effects of both optical efficiencies and angle modifiers, whereas the effect of the temperature was estimated separately through a MATLAB script. Both fixed array and fully tracking array were investigated in this work. The sizing of the PV water pumping system was carried out through a simple approach based on the daily hydraulic energy E_h required to lift the water demand, the average daily radiation on the plane of the array $I_{tot,d}$ and the overall system efficiency η_s. This approach is summed up in the following equation [19]:

$$P_{peak} = \frac{E_h}{I_{tot,d}\eta_s} \qquad (6)$$

The daily hydraulic energy was estimated from the daily water demand and hydraulic head with the following formula:

$$\mathrm{E_h} = \rho g H W_g \qquad (7)$$

Where ρ is the water density and g is the gravity acceleration. In Equation 7 W_g is expressed in m^3/ha day (1 mm/day corresponds to 10 m^3/ha day). The efficiency of the system takes into account the efficiency of the MPPT system, controller or inverter, electric engine, centrifugal pump and system losses [20, 21].

3.4 DC/DC converter-motor-pump

The model used in this work for the converter and inverter was based on the assumption that the output power is equal to the input power from the photovoltaic generator less the unavoidable power losses associated. Normally the efficiency varies between the 80% up to the 95 % depending on working conditions, especially temperature, and power available. The power losses were taken into account on the basis of an average efficiency of the power controlling system.

The motor-pump was sized on the basis of instantaneous water flow, estimated from daily water demand and daily operating hours, and hydraulic discharge. The total dynamic head was calculated taking into account several contributions such as outlet minimum pressure required by the irrigation system, height of the of the outlet pipe above the ground surface, depth of the static water level, depth of the dynamic water level and friction losses due to the pipeline circuit. In this study a hydraulic discharge measured in field tests was used. The sizing of the centrifugal motor-pump in kW was carried out with the following equation:

$$P = \frac{\rho g Q H}{1000 \eta_p} \quad (8)$$

Where, Q is the flow expressed in m^3/s, *1000* is a conversion factor and η_p is the efficiency of the motor pump system.

The motor-pump system was modeled on the basis of the governing equations of the electric engines, affinity laws and hydraulic power. The main input data regarding the minimum and maximum head and the corresponding flows and efficiencies, were taken from motor-pump datasheet provided by pumps manufacturer companies [22, 23]. The dynamic modeling of the pump was carried out considering the pump characteristic curve that expresses the instantaneous water flow in m^3/h versus the hourly feeding power to the motor-pump system. A typical expression of the relationship between water flow Q, hydraulic discharge H and power input P_{in} is given by the following third grade polynomial:

$$Q(H, P_{in}) = c_1(H) P_{in}^3 + c_2(H) P_{in}^2 + c_3(H) P_{in} + c_4(H) \quad (9)$$

Where, c_1, c_2, c_3 and c_4 are experimental coefficients. The previous curves, both for the DC and AC pump, were obtained from PVsyst (v5.55) through the specific tool for pumping system and adjusted with the curve fitting function in MATLAB.

4. RESULTS AND DISCUSSIONS

This section shows the results regarding the assessment of water demand and solar energy, sizing and modeling of the system, matching between water demand and water supply and economics analysis between DC and AC pump and fixed and fully tracking PV array. In this work an irrigated area of 1 ha was considered.

4.1 Assessment of the water demand

The monthly average water demand for the growing of Alfalfa on a sandy soil and the trend of the monthly average precipitation are presented in Figure 3.

Figure 3: Monthly average daily water demand.

It is clear that the trend of the daily water demand for irrigation is affected mainly by the evaporation related to the growing phase and rainfall. The evapotranspiration registered a peak during the sunniest months of the year whereas the precipitation registered the highest values in the period May-September. The irrigation season for the crop chosen is five months, this study interested then only the months from May to September. In this work it was assumed that in May takes place the development phase, in June and July the intermediate phase and in August and September the final phase. The Alfalfa water demand trend shows then a peak during the month of June of 47 m^3/ha and it decreases during the remaining months. The minimum daily water demand estimated for this period corresponded to the water requirements in May which is equal to 10.4 m^3/ha. The irrigation turn estimated by the model was 10 days. In this work an irrigated area of 1 ha was considered. The validation of the results obtained from the water demand model was carried out through personal communication with field expert and with the results obtained in field studies conducted in the same region [24]. The former proved that the daily maximum water requirement for irrigation is 50 m^3/ha. Whereas the results obtained in previous field studies showed an irrigation duty of 600 m^3/ha for an irrigation turn of 14 days corresponding to 40 m^3/ha day.

4.2 Solar energy assessment

The available solar radiation and its variation with the tilt angle and system technology are shown in Figure 4. In this study it was assumed to use a fixed system with an azimuth angle equal to 0° that corresponds to solar array oriented towards south. The results of the simulations show that for the fixed system the best tilt angle on annual basis was 30° with a corresponding collectable solar radiation of 1870 kWh/m^2 year. For the simulations carried out only during the irrigation season, from May to September, the best tilt angle resulted in 10° collecting 854 kWh/m^2 season. The 10° tilted solar array was then used in our study. As regards the fully tracking system, the annual collected solar radiation on the plane surface was 2490 kWh/m^2 year whereas 1120 kWh/m^2 during the irrigation season. This corresponds to a collected solar energy 30 % higher compared to the optimal fixed system.

Figure 4: Solar energy available depending on the tilt angle and system technology.

The power output from fixed and fully tracking PV system with a capacity of 1 kW_p during a sunny day in June is shown in Figure 5. The energy collected by the 10° tilted system was 7.0 kWh/m^2 whereas the solar energy collected by the fully tracking array it was equal to 10 kWh/m^2 corresponding to 40% more energy than the fixed system. The better performances of the sun fully tracking system are mainly due to the system, varying continuously its tilt and azimuth angle in order to follow the sun, optimizes the harnessing of available solar radiation guaranteeing a wider range of working hours at higher power output compared to the fixed system.

Figure 5: 1 Kw_p power output during a sunny day in June.

It is clear that the solar generator power output depends on the variation of the available solar power and is mainly sensitive to the variation of ambient temperatures. The typical effect of the hourly variation of ambient temperature on the power output of solar array is presented in Figure 6 for 1 kW_p PV array.

Figure 6: Effect of the temperature on the power output of 1 kW_p solar array.

The power output from the solar generator without considering the temperature effect, is the power at the reference temperature of 25 °C and depends only on the available solar radiation, PV modules optical efficiency and incidence angle modifiers. As it is shown, the temperature affects the power generation of the solar array during the sunniest and warmest hours of the day due to the difference between cell temperature and reference temperature. The maximum drop of the efficiency and the subsequent drop of power generation were registered at 1 pm and it was equal to 198 W representing a loss of 17 %. The high value of power waste was due to the theoretical approach used in this study to perform the effect of temperature on the PV modules efficiency. The previous approach tends to overestimate the power losses due to temperature, usually in the range of 10 %, on behalf of guaranteeing more accurate water supply forecasts.

4.3 Pump modeling

The sized PV systems were used in dynamic simulations in order to estimate the hourly power output and hourly water pumped. The dynamic modeling of the photovoltaic pumping system could further verify if the sized system could fulfill the dynamic water requirements. The water pumped under different PV power output was estimated on the basis of the pump characteristic curve flow rate against power input. Obviously, the instantaneous pumped water flow is mainly affected by the variation of the power coming from the solar array. Figure 7 shows the instantaneous water flow at different motor power input.

Figure 7: Instantaneous water flow compared to the power input to the motor.

In the case of the AC technology the engine starts to drive the pump when is reached a minimum feeding power of 0.37 kW. The instantaneous flow increases with the input power until reaching 1.5 kW. The motor-pump speed is governed in the above mentioned power range following the pattern outlined. For input power greater than 1.5 kW the speed and then the water output was kept constant and equal to the maximum due to the power conditioning system interface in order to avoid damages to the electric engine. In the case of the DC motor the power working range varies from 0.15 kW and 1.6 kW.

4.4 Sizing of the system

The sizing of PV array and pump was then made on the basis of the water demand, total dynamic head, solar energy available and efficiencies of the system. The system was sized on the basis of the worst month marked out by the lowest ratio between monthly daily average solar radiation and monthly daily average water demand, as shown in Table 2.

Table 2: Solar energy and water demand ratio.

June presented the lowest ratio between daily solar radiation and water demand especially due to the highest water requirements registered during the irrigation period. June was then chosen as designing month. According to the estimation of water demand, 47.1 m^3 of water is needed every day during the irrigation turn. The PV array peak power was estimated on the basis of the daily hydraulic energy required to achieve a hydraulic head of 40 m and the monthly average daily solar radiation. The resulting required hydraulic energy was 5 kWh/day whereas the resulting monthly average daily solar radiations were 6.0 kWh/m^2 and 7.8 kWh/m^2 for fixed system and fully tracking system respectively. The sizing procedure for the PV array peak power is also affected by the efficiencies of controller or inverter, electric engine, pump and other unavoidable system losses due mainly to power losses of PV modules affected by temperature variation and electric losses in the wires. All these contribution are summarized in the overall system efficiency η_s given by the following:

$$\eta_s = \eta_{pc}\eta_p\eta_{PV,T}\eta_w \tag{10}$$

Where η_{pc} is the efficiency of the power conditioning system, η_p is the efficiency of the pumping system and $\eta_{PV,T}$ and η_w consider the losses power losses in the PV modules and wires. These efficiencies vary with device models and working conditions. For example, the efficiency of the power conditioning system is affected mainly by the power input and ambient temperature varying between 80 % and 95 %, the motor pump efficiency varies from 40 % up to 60 % depending on power input, water flow and pressure. In this study, in order to take into account the effect of components efficiency on the system performances, three values of the system efficiency were tested in the design and subsequently proved through dynamic simulations: 30%, 35% and 40% respectively. This resulted in three different PV array sizes for both fixed and fully tracking installation. The resulting PV array power were 2.8 kW_p, 2.4 kW_p and 2.1 kW_p for the fixed system and 2.1 kW_p, 1.8 kW_p and 1.6 kW_p for the two-axes tracking system respectively. On the basis of the power peak obtained, the corresponding PV area was estimated assuming an energy conversion efficiency of the PV panels equal to 14.3 % [25]. The pump capacity was estimated according to the hydraulic head and the instantaneous water flow. The instantaneous water flow was estimated from the daily water demand assuming 8.5 operating hours. The required pump power resulted in 1.5 kW. According to the pumps available on the market, the following pumps were adopted: 1.6 kW DC centrifugal multistage and 1.5 kW AC single phase centrifugal multistage. The main input data and results of the designing phase are summarized in Table 3.

Table 3: Summary of the main system parameters and sizing results.

4.5 Design proving

Concerning the worst situation in June, the simulated pumped water was compared with the estimated daily water demand in order to identify the mismatches. The simulation step was set equal to the irrigation turn, 10 days, period marked out by a water demand of 470 m^3.

As the motor-pump system was driven by a 2.8, 2.4 and 2.1 kW_p fixed PV arrays, the pumped water during the first irrigation turn in June amounted to 515, 470 and 426 m^3 respectively when using the DC pump; while 599, 531 and 470 m^3 respectively when using the AC pump. Therefore, the system of AC pump can always satisfy the water demand. However, for the system of DC pump centrifugal pump, it has to be driven by a PV array larger than 2.4 kW_p in order to achieve the pumped water could match the water demand. For the case of DC centrifugal pump driven by 2.1 kW_p PV array the mismatch was 44 m^3. The achieved results through dynamic simulations for the fixed PV systems are presented in Figure 8.

Figure 8: Pumped water flow during an irrigation turn in June with fixed PV array.

As the solar arrays mounted on the two-axis tracking system, the amounts of pumped water in June were calculated as 546, 492 and 448 m^3 for the 2.1, 1.8 and 1.6 kW_p respectively when using DC pump; while 634, 553 and 486 m^3 respectively when using AC pump. It is similar the situation of fixed PV system that the system of AC pump can always satisfy the water demand. For the system of DC pump, the PV array has to be larger than 1.8 kW_p. The better performances of the AC pump compared with the DC were mainly due to the specific characteristic curve power input against instantaneous water flow. Although the DC pump is marked out by a less required power input to start running the pump and a higher rated power compared to the AC pump, the latter is featured by a higher water flow output for input power greater than 0.7 kW resulting in greater volume of water pumped. The dynamic simulations results for the sun tracking PV systems are presented in Figure 9.

Figure 9: Pumped water flow during an irrigation turn in June with tracking PV array.

It is clear that the overall efficiency used in the sizing phase affected the amount of pumped water. The achieved results show that a suitable design of the DC pumping system driven by the fixed PV array is based an overall efficiency of both 30% and 35%. These efficiencies permitted during the dynamic simulation to achieve the amount of water needed for the irrigation purposes. Efficiency equal to 35 % permitted to both fulfill the water requirements and minimize the PV modules area optimizing the system. Even in the case of DC pumping system driven by the fully tracking PV array, both 30% and 35% were suitable efficiencies for the designing of the system. In the case of the AC pump powered by the fixed solar array, the optimization of the system was achieved by an efficiency of 40 % considered during the design process both for the fixed and fully tracking PV array. It has to be pointed out that it doesn't imply that the high system efficiency is not desirable. The reason that the high efficiency system (40%) has a worse performance is mainly due to that the efficiency considered in the design stage is a based on steady performance. However, in order to represent the dynamic characters of both the climatic conditions and the system components, dynamic efficiencies may be required. Therefore, it is of great importance to conduct the dynamic simulation to prove the design and find the optimal value. Meanwhile, the overall system that accounts for the components dynamic efficiencies and, as the achieved results show, the optimal value can be set only through dynamic simulations need to be included in the future study to have a more accurate simulation.

The water output simulations were extended to the whole irrigation season as well, from May to September, comparing the crop variable water demand depending on the growing phase with the variable water supply due to the variation of available solar energy. Both DC and AC pump technology and optimal fixed and sun tracking array were used in these simulations. The monthly results about water demand and water supply are shown in Figure 10. Since that the water pumping system was sized for the worst month, there was then a surplus of pumped water during the months featured by a higher solar energy and water demand ratio than the corresponding designing month. Indeed, the water demand for Alfalfa varies during the irrigation season depending on the crop growing period. Simultaneously the available solar radiation varies during the irrigation season affecting the power output and then the pumped water.

Figure 10: Monthly water demand and supply estimated through dynamic simulations.

Moreover, when extending the simulations to one month instead of within one irrigation turn (ten days), some critical situations occur. It is clear from Figure 10 that both DC and AC driven by tracking PV array could fulfill the water requirements in June. However, when fixed PV array is used, some mismatching between water supply and water demand were identified: 13 m^3 for the DC pump system driven by 2.4 kW_p PV array and 24 m^3 for the AC pump system driven by the 2.1 kW_p PV array. The mismatching identified in the monthly simulation was the result of the dynamic variability of solar radiation affecting the water output from the pumping systems. As shown in

Figure 11, days marked out by poor solar energy conditions can considerably affect the amount of pumped water but without substantially affecting the water demand since the latter depends on more climatic parameters, such as humidity, wind and rainfall. Moreover, in periods or months marked out by lower solar energy, such as September, systems using DC pump technology offered better performances in terms of water supply due to the lower power input requirements.

The surplus of pumped water recorded during the irrigation season could be used in order to extend the irrigated area or for other purposes in order to use the system more effectively. For example, if the surplus of water is used for irrigation, for the AC pump system driven by the 1.6 kW_p PV tracking array, the irrigated area can be extended up to 4.9 ha when it is in May and 1.7 ha in August and September; while for the DC pump system driven by 1.8 kW_p PV tracking array, the irrigated area can be extended to 4.7 ha in May and 1.7 and 1.8 in August and September respectively.

Figure 11: Hourly dynamic simulations of water demand and water supply from AC pump powered by 2.1 kW_p solar array.

4.6 Economic analysis

An economic analysis based on the investment costs was carried out in order to investigate the most cost effective solution among the alternatives presented in this study especially between system equipped with fixed and sun tracker array and AC and DC pump technology. This analysis was performed in order to combine both economic aspects and performances in terms of water pumped according to the crop water requirements previously discussed.

The prices of the PV modules are highly variable depending on the market and the manufacturer company. Nevertheless it represents one of the major costs for a photovoltaic pumping system, accounting for more than the 30 % of the overall costs (considering in the economic analysis the cost of well digging). Using the sun tracking system permits a smaller area of PV modules which resulted in a deducted capital cost of PV cells and power conditioning system. But at the same time the tracker can highly contribute on the overall cost of the system mainly due to its high accuracy technology. Moreover, DC pump are more expensive compared to AC pump but on the contrary the controller used as interface between the PV modules and the DC electric engine is more affordable then DC/AC inverter. Comparing the 1.8 kW_p two-axis tracking system with the 2.4 kW_p fixed solar array powering the DC pumping system, although the tracking system has a power peak about 30% less than the fixed system, the former offers better performances than the latter due to the daily higher exploitability of solar energy. The AC pump driven by the fixed 2.1 kW_p PV array fulfilled the water requirements as the DC pump powered by the fixed 2.4 kW_p solar generator saving 0.3 kW_p of solar cells. Even the AC pumping system powered by the 1.6 kW_p solar generator mounted on the tracking system fulfilled the water requirements avoiding the installation of 0.8 kW_p of solar cells compared to the DC 2.4 kW_p fixed system and 0.5 kW_p of PV modules compared to the AC 2.1 kW_p fixed system.

The PVWPS systems compared in terms of initial investment costs (IIC) in this economic analysis were the same systems compared in terms of water pumped in the previous section of this paper. The possibility to install tracking system instead of fixed system and DC instead of AC pump was estimated. All the prices used in the investigation, summarized in Table 4, were taken from a business-to-business online platform and refer to the Chinese market [16].

Table 4: PV water pumping system components unit costs.

The results of the economic analysis are presented in Figure 12, outlining the total initial capital cost together with the costs contributions.

Figure 12: Total initial investment costs for the PVWPS proposed.

On the basis of the economic investigation carried out, the most cost effective solution was the AC 2.1 kW_p fixed system with an overall initial capital cost of 2450 \$ followed by the DC 2.4 kW_p system marked out by an initial capital cost of 2950 \$. The reason that the DC fixed system has a higher investment compared with the corresponding AC fixed system was mainly due to the cost difference of DC and AC pump, 640 \$ against 150 \$, rather than the cost difference of PV modules, 1440 \$ against 1260 \$. Despite of the reduction in cost due to the installation of DC/DC converter on behalf of the installation of DC/AC inverter, the AC fixed system was the most cost-effective solution. Comparing the fixed system with the corresponding systems equipped with the sun tracker device, the formers presented lower investment cost than the latter especially because of the high investment cost due to the tracking system. The tracked DC 1.8 kW_p system had an investment cost of 4350 \$ of which 1620 \$ were due to the sun tracking device accounting for 37 % of the overall cost. The cost reduction due to the lower investment in PV modules and power conditioning system using sun tracking technology had no positive effects. A possible application of PVWPS equipped with solar tracker could be economically supported in the case the system is used for multipurpose applications during the months where the irrigation is not needed.

5. CONCLUSIONS

In this study a dynamic simulation tool combining the models of the water demand, the solar PV power and pumping system was developed in order to be used for quick design and design validation. According to the achieved results the following conclusion can be pointed out:

- The sizing of photovoltaic water pumping systems for irrigation is extremely affected by the dynamic character of the water demand and collectable solar energy. In order to define the worst condition on the basis of which the system is sized, the lowest ratio between required hydraulic energy and available solar radiation has to be considered.

- The assessment of the overall system efficiency η_s is relevant to optimally size the PV array power peak avoiding both system failure and economic losses. η_s summarizes in a steady value the dynamic efficiency of the system components and the optimal value can only be set through system dynamic simulations verifying the match between pumped water and water demand.
- Preliminary economic analysis based on the initial investment costs showed that AC pump powered by fixed PV array represent the most cost-effective solution for water pumping.

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Figure captions

Figure 1: Schematic diagram of a photovoltaic water pumping system.

Figure 2: Designing and dynamic modeling procedure.

Figure 3: Monthly daily estimated water demand.

Figure 4: Solar energy available depending on the tilt angle and system technology.

Figure 5: 1 Kw_p power output during a sunny day in June.

Figure 6: Effect of the temperature on the power output of 1 kW_p solar array.

Figure 7: Instantaneous water flow compared to the power input to the motor.

Figure 8: Pumped water flow during an irrigation turn in June with fixed PV array.

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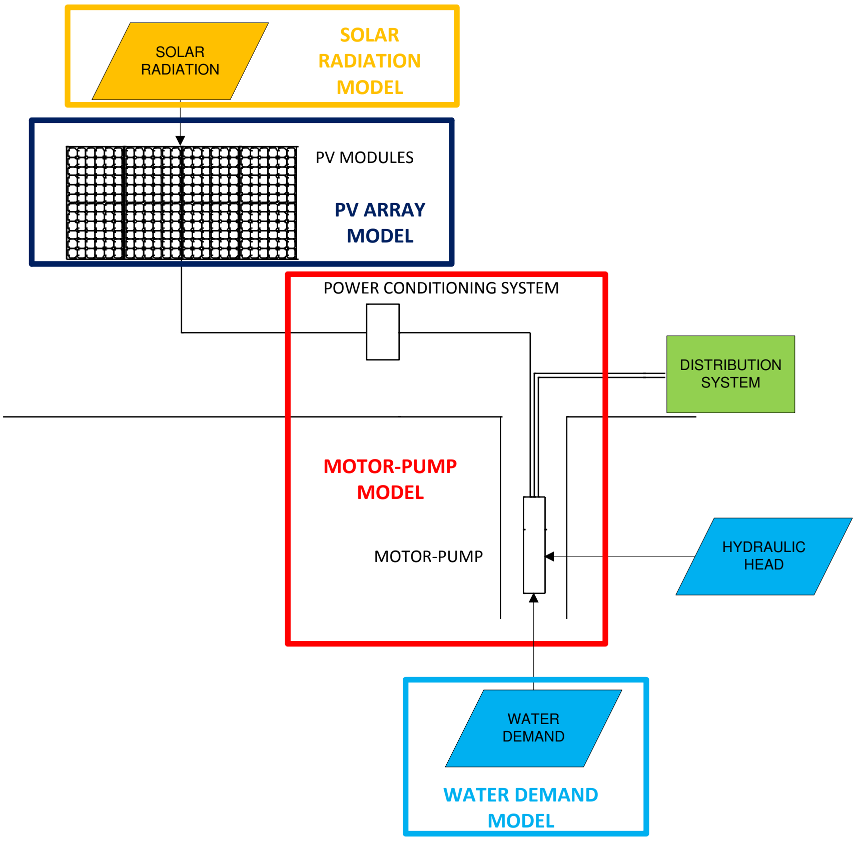

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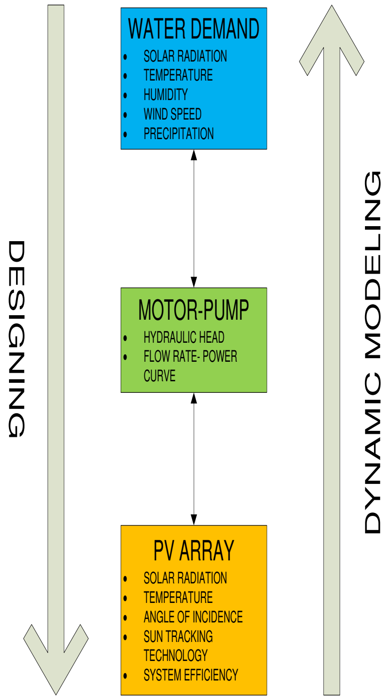

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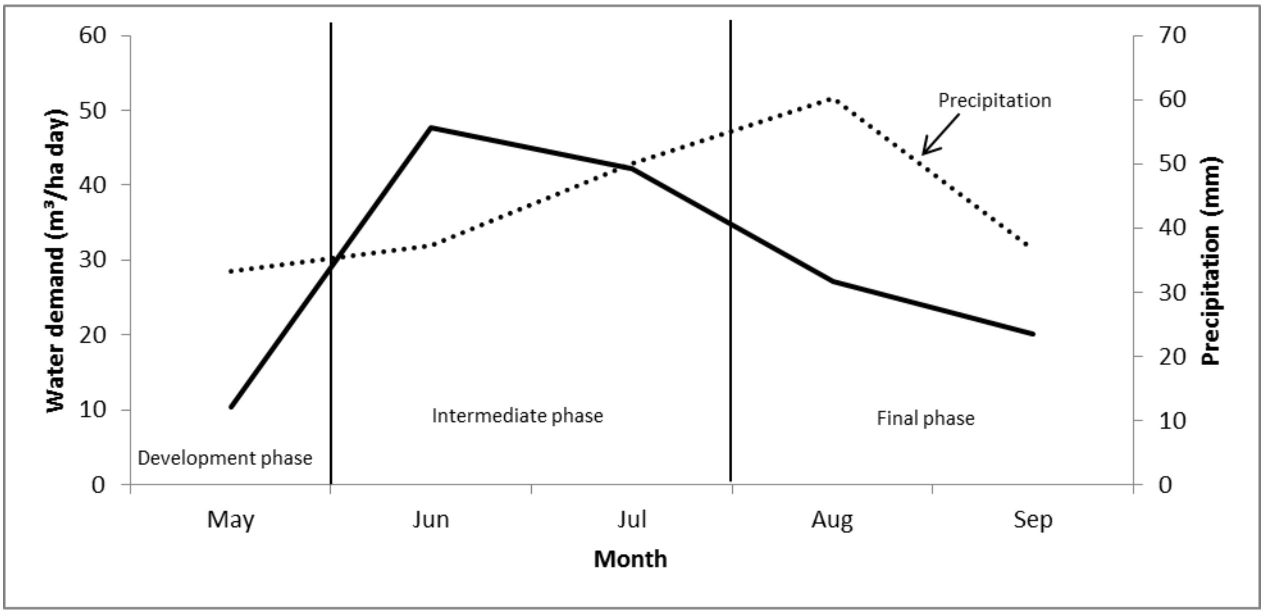
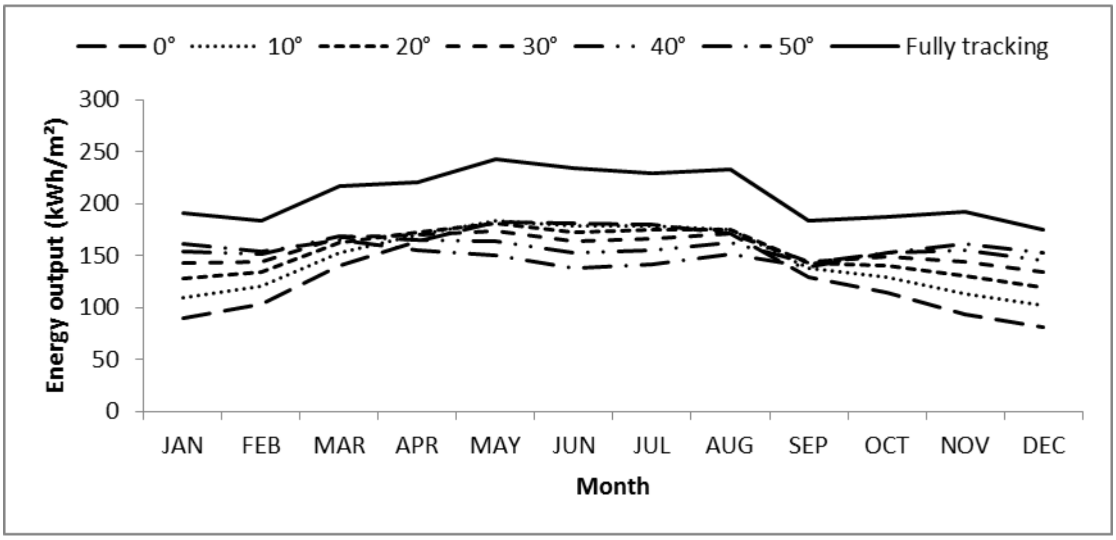


Figure 3: Monthly average daily water demand.



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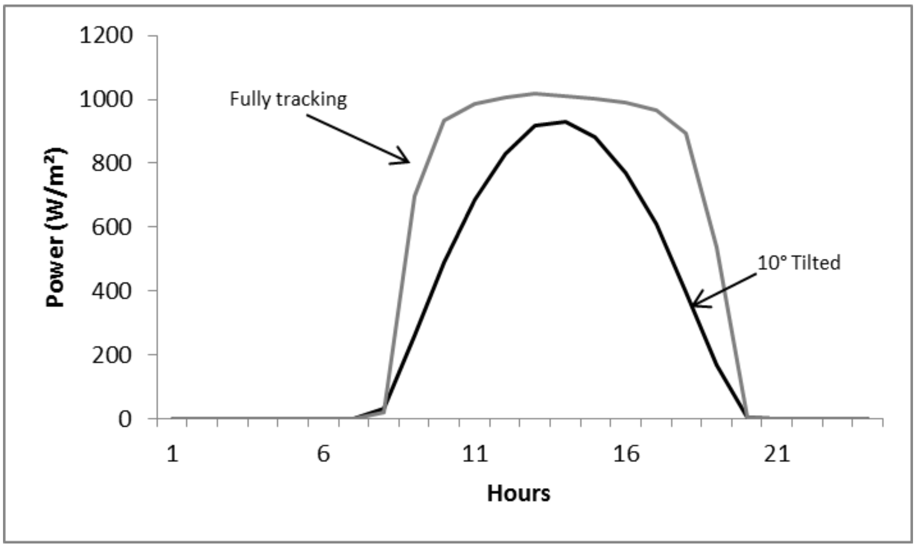

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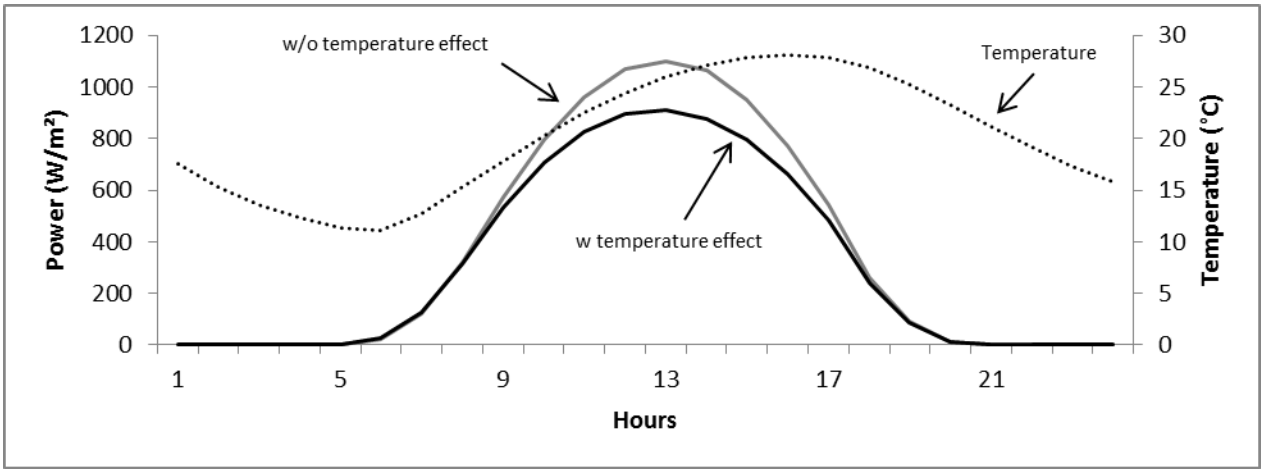

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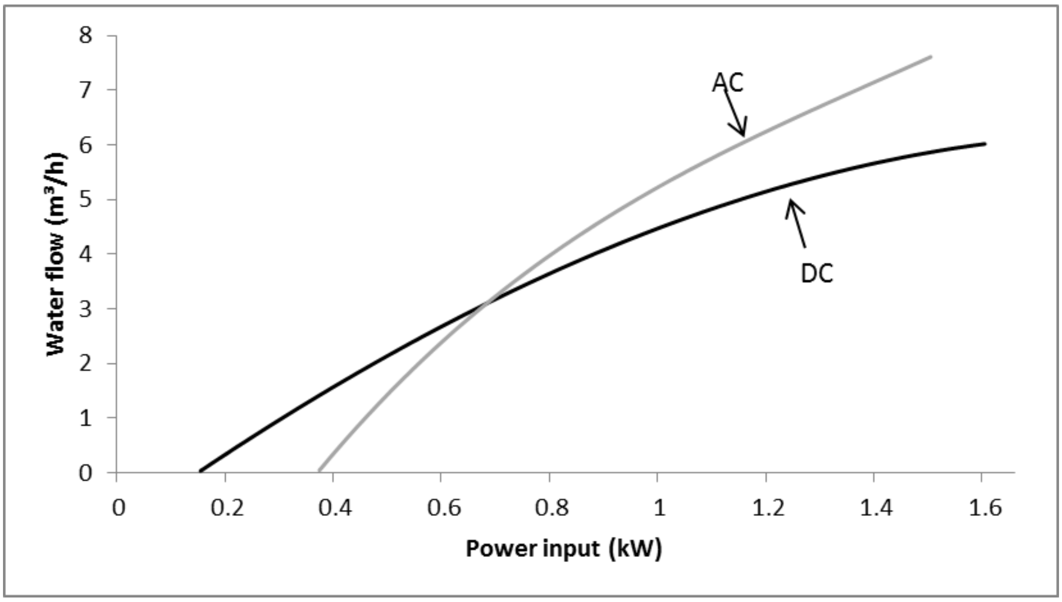

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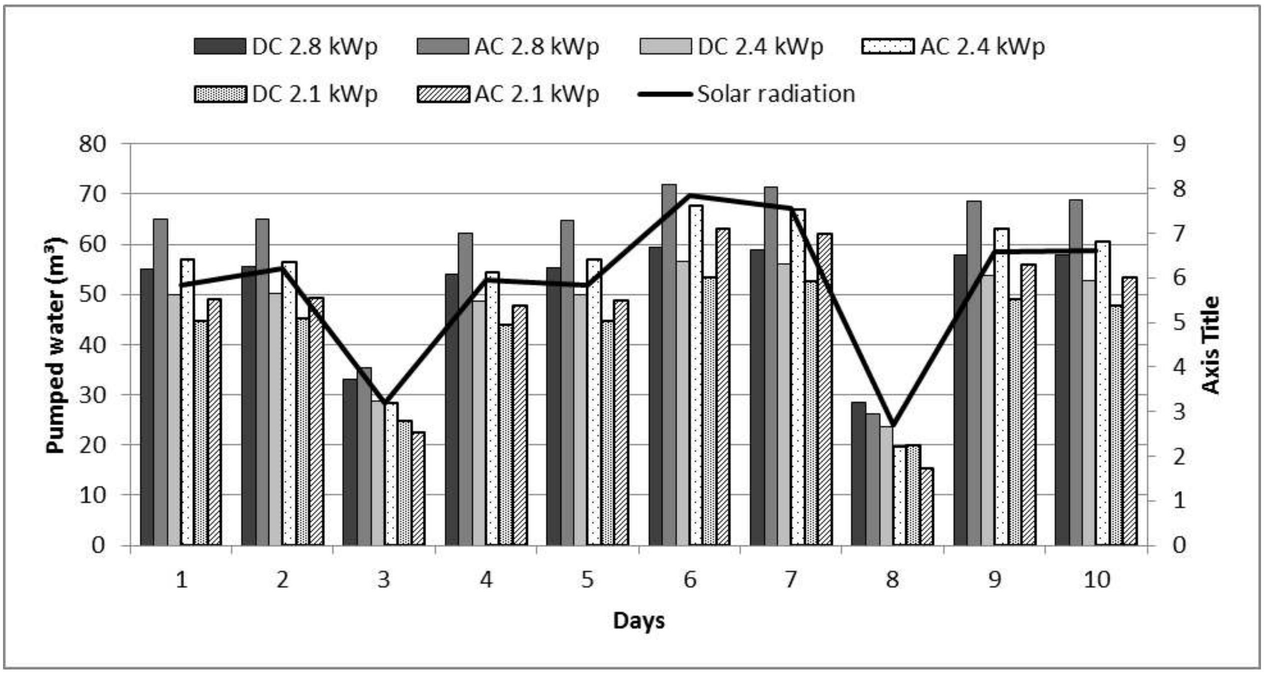

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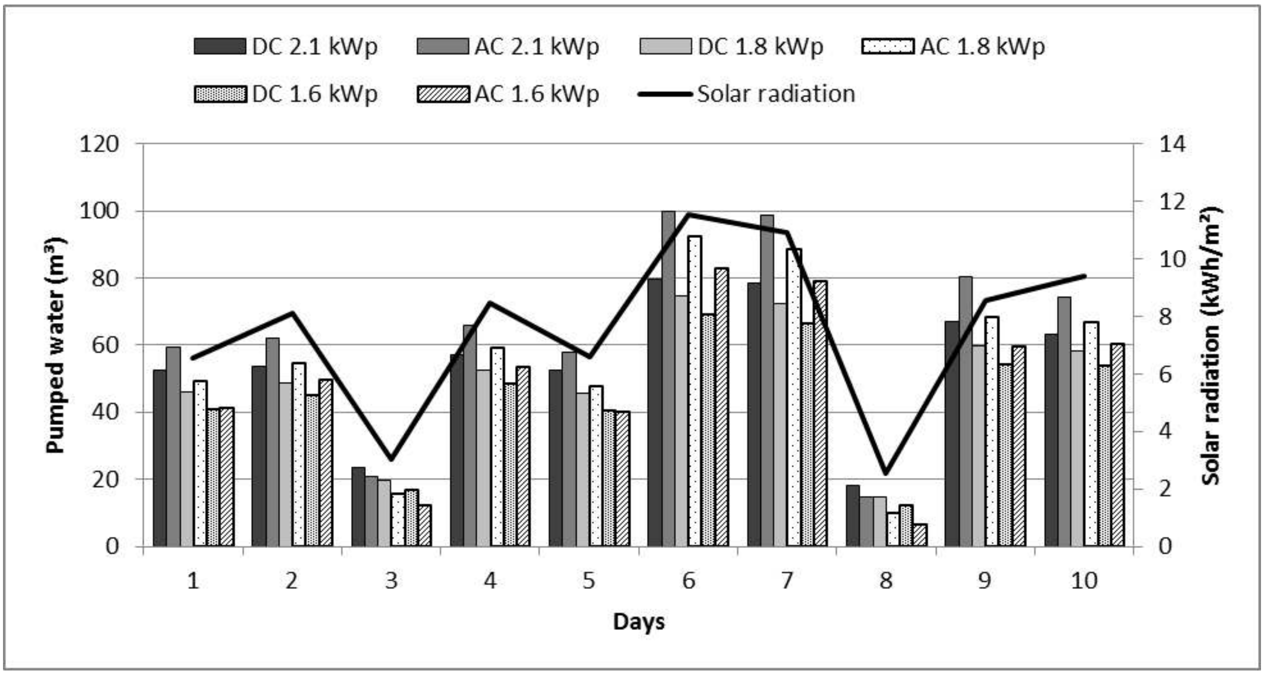
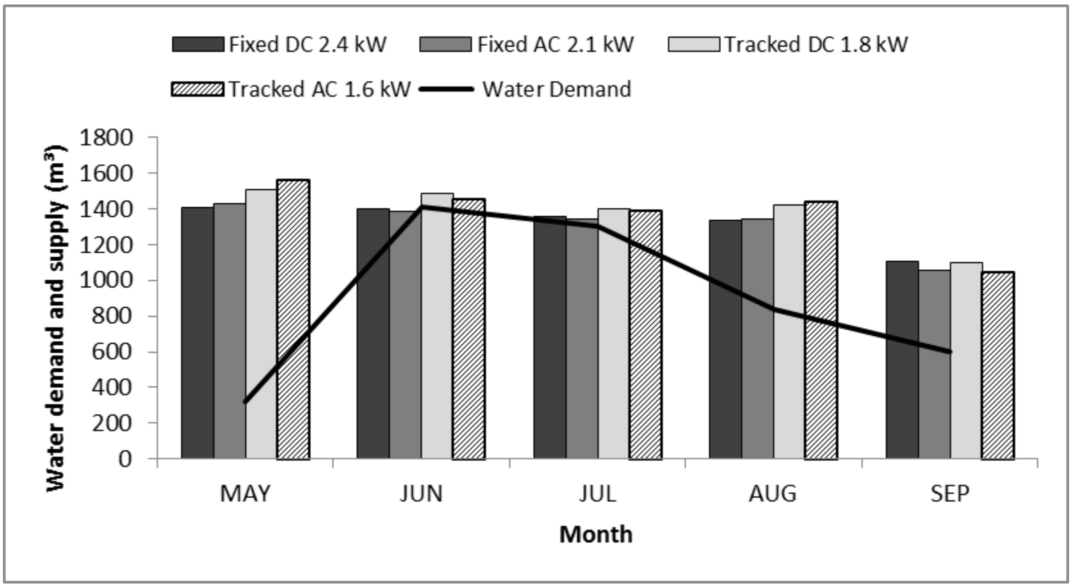


Figure 9: Pumped water flow during an irrigation turn in June with tracking PV array.



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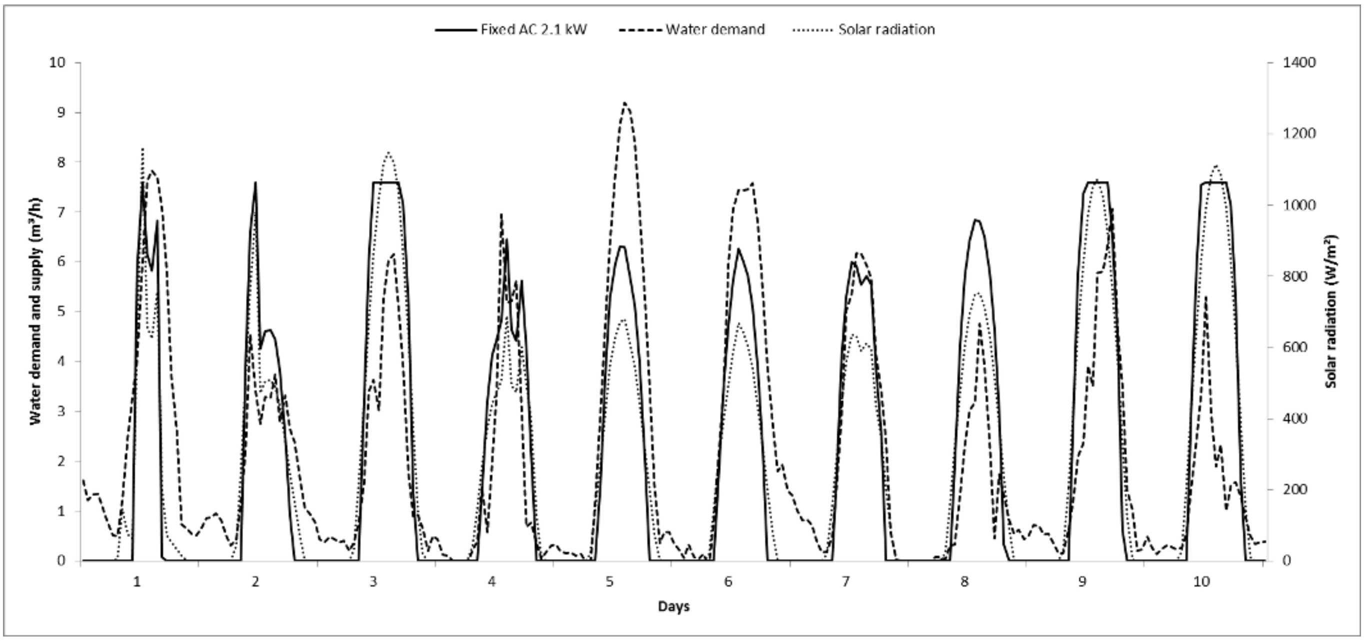

Figure 11: Hourly dynamic simulations of water demand and water supply from AC pump powered by 2.1 kW$_p$ solar array.

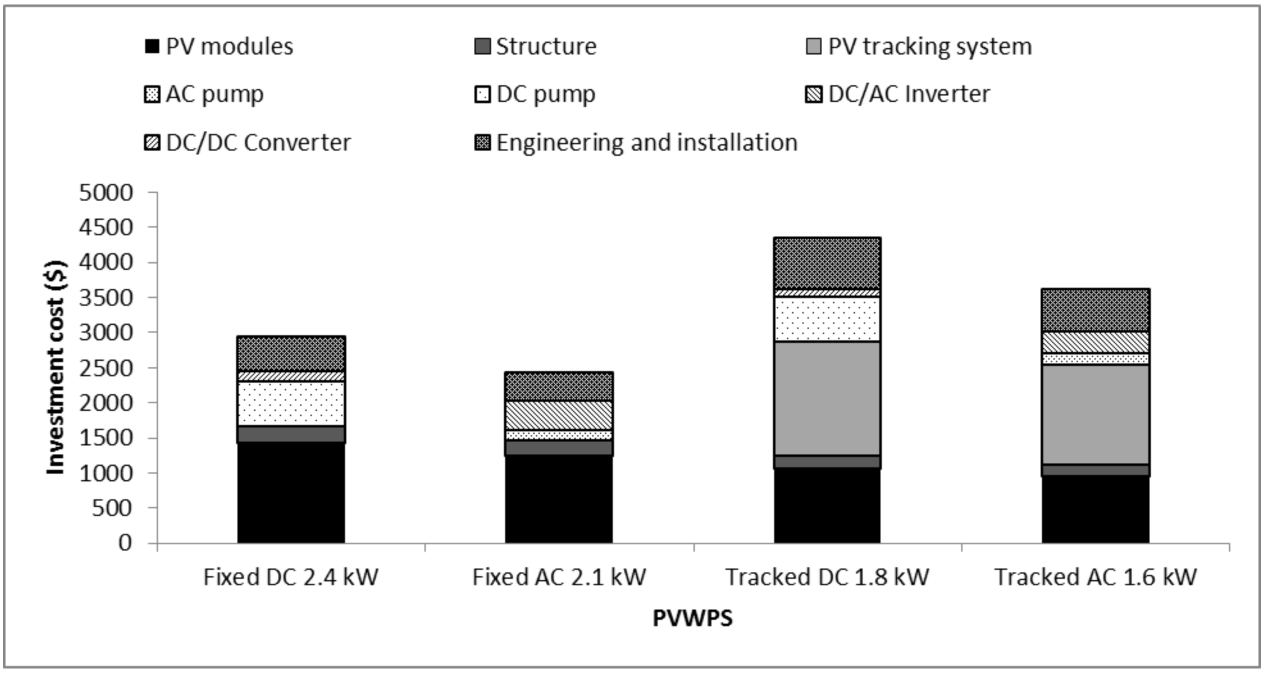

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Table captions

Table 1: Climatic data for Xining.

Table 2: Solar energy and water demand ratio.

Table 3: Summary of the main system parameters and sizing results.

Table 4: PV water pumping system components unit costs.

Table 1: Climatic data for Xining.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
T (°C)	-6.0	-2.0	5.0	11.6	16.8	19.8	22.2	21.1	15.5	9.7	1.9	-4.8
RH (%)	65.6	65.0	60.5	57.6	56.5	60.6	65.5	67.4	66.9	63.6	65.3	70.2
P (mm)	0.7	3	8.3	16	33.3	37.3	50	60.2	36.6	18.7	4.5	0
WS (m/s)	2.8	3.0	3.6	3.7	3.7	3.2	3.0	2.9	2.8	2.9	3.1	2.9
GH (kWh/m^2)	75.6	96.6	144.3	168.5	182.2	187.2	184.5	157.7	127.5	89.3	76.1	53.5
EX (kWh/m^2)	149.8	176.3	253.0	297.8	344.6	346.7	349.7	319.4	262.8	212.8	156.9	136.8
LI (kWh/m^2)	160.9	156.4	195.4	210.8	239.0	247.2	269.0	267.1	235.9	219.5	184.0	170.6
LO (kWh/m^2)	209.3	204.3	254.6	272.5	303.3	306.6	326.0	319.6	285.5	269.4	232.2	212.9

Table 2: Solar energy and water demand ratio.

	May	June	July	Aug	Sept
I_{tot} (kWh/m^{2}day)	5.9	6.0	5.8	5.7	4.6
W_g (m^3/ha day)	10.4	47.1	42.0	27.0	20.1
Ratio (%)	56.7	12.9	14.4	21.1	22.8

Table 3: Summary of the main system parameters and sizing results.

Water demand (m3/ha/day)		47.1	
Irrigated area (ha)		1	
Daily operating hours		8.5	
Total dynamic head (m)		40	
Pump power (kW)		1.5	
Average monthly daily solar radiation on fixed system (kWh/m^2)		6.0	
Average monthly daily solar radiation on tracking system (kWh/m^2)		7.8	
PV module efficiency in STC (%)		14.3	
NOCT (°C)		47.2	
Power temperature coefficient (%/°C)		-0.45	
Efficiency of the system (%)	30	35	40
Fixed system power peak (kW_p)	2.8	2.4	2.1
Fixed system array area (m^2)	20	17	15
Tracking system power peak (kW_p)	2.1	1.8	1.6
Tracking system array area (m^2)	15	13	11

Table 4: PV water pumping system components unit costs.

Component	Unit cost
PV modules	0.6 $/W_p$
Structure	0.1 $/W_p$
PV tracking system	0.9 $/W_p$
DC/AC Inverter	0.2 $/W_p$
DC/DC Converter	0.06 $/W_p$
AC pump	0.1 $/W
DC pump	0.4 $/W
Engineering and installation	20 % (IC)