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A METHOD FOR ESTIMATING THE LONG-TERM PERFORMANCE OF DIRECT-COUPLED PV PUMPING SYSTEMS

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Abstract—A method is developed to predict the long-term performance of direct-coupled PV pumping systems. The method uses only information available from the PV module and pump-motor manufacturers. Weather data are "generated" from monthly averages of horizontal radiation and ambient temperatures using well-known weather data statistics. The method predicts monthly pumped water to within 6% of TRNSYS predictions based on hourly weather data. The use of a single monthly-average day is shown to underpredict monthly pumped water at low monthly average radiation levels and overpredict monthly pumped water at intermediate radiation levels. Only at high radiation levels does the use of a single monthly-average day provide a reasonable estimation of monthly pumped water. © 1998 Elsevier Science Ltd. All rights reserved.

1. INTRODUCTION

The use of photovoltaics for water pumping is appropriate as there is often a natural relationship between the availabilty of solar energy and the water requirement. The water requirement increases during hot weather periods when the solar radiation levels are highest and the output of the solar array is at a maximum. Photovoltaic water pumping systems (PVPS) are particularly suitable for water supplies in remote areas where no reliable electricity supply is available. Photovoltaic-powered livestock watering is gaining in popularity with electric utilities in remote areas. Utilities are finding it more economical to use a photovoltaic-powered pump than to provide and maintain a distribution line to a remote pump. The cost of photovoltaic installations is mostly dependent on the PV array area. The major disadvantages of using PV are the high installation costs and its low energy conversion efficiency. Significant cost penalties result from oversizing a PV system. Therefore, in order to improve the cost effectiveness of PV array powered systems, the electric power generated by the PV array should be efficiently utilized.

Three-different PV system configurations are currently in use. The most efficient configuration uses a maximum power point tracker (MPPT) to maintain the PV array at a voltage for which it produces its maximum power, the voltage is then changed by an inverter to that needed by the load. In a battery buffered system, a battery is connected across the array to store energy and to provide a nearly constant voltage load. A proper choice of operating voltage for the battery and load can produce efficiencies close to that of a MPPT system. Finally in a directly coupled system, a PV array is directly coupled to a DC motor and pump. Direct-coupled systems are simple and reliable, but do not operate at the maximum power operating point of the array, due to the continuous variation of solar radiation. Direct-coupled systems are the subject of this investigation.

The difficulty in predicting the performance of a direct-coupled PV pumping system is as follows: when the PV array supplies sufficient electrical power, the motor produces mechanical torque and the pump draws water. Sufficient radiation must be available for a PV pumping system to start its pumping operation; this radiation level is called the radiation threshold. The threshold of a PV pumping system depends on the characteristics of the system components. After the pump starts, it will pump water at a rate that depends on the intensity of the radiation. There is a nonlinear relationship between pumping rate and the radiation; at high radiation levels, the rate of increase of the pumping rate with increasing radiation is smaller than at intermediate radiation levels. Both the existence of a radiation threshold and the nonlinear dependence of flow on radiation level complicate the prediction of direct-coupled PV pumping system performance.

Both experimental and analytical studies have investigated and proposed different methods for designing and optimizing the PVPS to improve the system efficiency and reduce the investment. Appelbaum and Bany (1979a,b) analyzed a direct-coupled PV pumping system under steady state conditions. Singer and Appelbaum (1993) have examined the starting characteristics of PV powered DC motors and pumps both with and without MPPT. Roger (1979) showed that a DC motor driving a centrifugal pump represents a well-matched load for a PV array because this system utilizes most of the DC power generated by the array. Anis *et al.* (1985) reported that a load composed of a DC motor driving a constant volume pump represents a non-matched load to a PV array because the motor driving a constant volume pump requires a nearly constant current. The matching of a DC motor to a PV generator to maximize daily gross mechanical energy is reported by Saied and Jabori (1989). Salameh and Taylor (1990) have analyzed the effect of PV array configuration on the performance of PVPS. Hsiao and Blevins (1984) and Koner *et al.* (1992) analyzed the performance of PVPS by varying the motor characteristics. In the study by Hsiao and Blevins (1984), hourly radiation data for a year were required, leading to extensive use of computer simulation time. Dunlop (1988) has experimentally investigated the effects of different tracking methods. In the study of solar radiation utilization by Loxsom and Durongkaveroj (1994), two straightline segments were used to represent the nonlinear flow rate versus radiation relationship.

Townsend (1989), Eckstein (1990), and Al-Ibrahim (1996) developed a comprehensive PV cell model for the TRNSYS simulation program (Klein *et al.*, 1996) which uses four parameters. They also developed motor, pump and MPPT models. However, the nonlinear relationship among these models is complicated, requiring numerical skill to successfully simulate systems over extended time periods. In addition, it is difficult to obtain the necessary input parameters for the motor and pump models based on available data.

The objective of this research is to develop a general method for the evaluation of long-term performance of a direct-coupled PVPS. The method is based only on information normally supplied by the manufacturers of the PV module and the pump-motor unit. The simulation is done on an hourly basis, but it uses well-established weather data statistics to reduce the calculation time and eliminate the problem of obtaining the long-term average hourly weather data.

2. THE PV CELL MODEL

A PV module is a nonlinear power source. The output current and voltage depend on the radiation level and temperature as shown in Fig. 1. Whenever the solar radiation or ambient temperature changes, the operating point of the PV module coupled to a pump-motor will change. Figure 1 also shows a typical pump-motor *I–V* curve and the corresponding operating points.

To predict the performance of a PVPS, a mathematical solar cell model is needed. The solar cell can be represented by the equivalent circuit shown in Fig. 2 [see for example Loferski (1972)). The relationship between current, I, and voltage, V, is:

$$I=I_L-I_o\left[\exp\left(\frac{V+IR_s}{A}\right)-1\right]-\frac{V+IR_s}{R_{sh}}, \tag{1}$$

where: I_L = light current (A); I_o = dark current (A); I = operation curtent (A); V = operation voltage (V); R_s = series resistance (Ω); R_{sh} = shunt resistance (Ω); A = thermal voltage (V).

I_L, I_o, R_s, R_{sh}, and A are five parameters that depend on the incident solar radiation and the cell temperature. Townsend (1989), Eckstein (1990) and Al-Ibrahim (1996), proposed a four parameter model which neglects the shunt resistance R_{sh} since it is usually very large compared

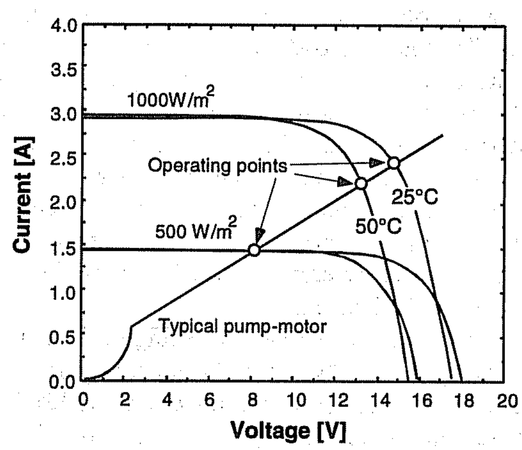

Fig. 1. The *I–V* curves of a PV Module and a pump-motor for two radiation levels and two temperatures showing the corresponding operating points.

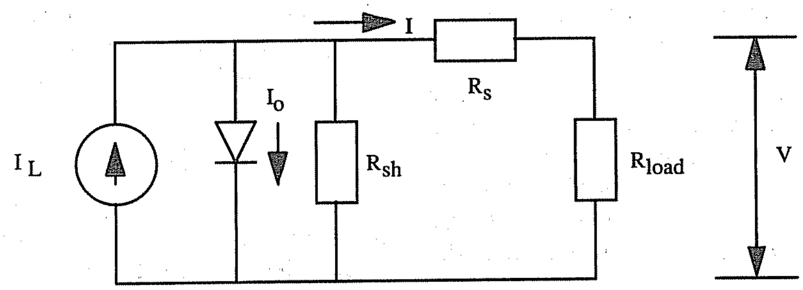

Fig. 2. Equivalent circuit of a solar cell.

with the series resistance R_s, particularly for single crystalline silicon cells. With this assumption, eqn (1) can be rewritten as:

$$I=I_L-I_o\left[\exp\left(\frac{V+IR_s}{A}\right)-1\right]. \quad (2)$$

A method to calculate these four parameters (I_L, I_o, R_s, and A) is summarized in Duffie and Beckman (1991). Since there are four unknown parameters, four conditions of I and V are needed. However, manufacturers usually provide I and V at only three conditions: short circuit, open circuit and maximum power point. The fourth condition comes from the knowledge of μ_{Voc} and μ_{Isc}, the temperature coefficients of open circuit voltage and short circuit current, respectively. Equations (3)–(6) are used to calculate these parameters of PV cells at a standard condition based on the experimental data provided by the manufacturer.

$$I_{L,\,ref}=I_{sc,\,ref}, \quad (3)$$

$$I_{o,\,ref}=\frac{I_{L,\,ref}}{\exp\left(\frac{V_{oc,\,ref}}{A_{ref}}\right)-1}, \quad (4)$$

$$R_{s,\,ref}=\frac{A_{ref}\ln\left|\left(1-\frac{I_{mp,\,ref}}{I_{L,\,ref}}\right)-V_{mp,\,ref}+V_{oc,\,ref}\right.}{I_{mp,\,ref}}, \quad (5)$$

$$A_{ref}=\frac{\mu_{Voc}T_{c,\,ref}-V_{oc,\,ref}+E_qN_s}{\frac{T_{c,\,ref}\mu_{Isc}}{I_{L,\,ref}}-3}. \quad (6)$$

The subscripts oc, sc, mp, and ref refer to open circuit, short circuit, maximum power and reference conditions, respectively, E_q is the band gap of silicon, (eV) and N_s is the number of cells in series in one module.

Whenever the solar radiation, G, or the ambient temperature, T_c, changes, the cell parameters change and can be estimated from the following equations. The cell temperature is obtained from the manufacturer supplied NOCT (Nominal Operating Cell Temperature) conditions (Duffie and Beckman, 1991).

$$T_c=T_a+\frac{G_T}{G_{T,\,NOTC}}(T_{c,\,NOTC}-T_a)(1-\eta_c/\tau\alpha), \quad (7)$$

where τ is the cell cover transmittance (if it exists) for solar radiation, α is the cell absorption for the transmitted solar radiation and η_c is the cell efficiency at NOCT conditions.

The cell parameters at the operating cell temperature and solar radiation are then found from:

$$I_L=\left(\frac{G}{G_{ref}}\right)[I_{L,\,ref}+\mu_{Isc}(T_c-T_{c,\,ref})], \quad (8)$$

$$I_o=I_{o,\,ref}\left(\frac{T_c}{T_{c,\,ref}}\right)^3\times\exp\left[\left(\frac{N_sE_q}{A}\right)\left(1-\frac{T_{c,\,ref}}{T_c}\right)\right], \quad (9)$$

$$R_s=R_{s,\,ref}, \quad (10)$$

$$A=A_{ref}\frac{T_c}{T_{c,\,ref}}. \quad (11)$$

The cell model is summarized as follows: eqns (3)–(6) are used to find values of the four parameters at reference conditions. These four parameters are corrected for environmental conditions with eqns (7)–(11) and used in eqn (2) which relates cell current to cell voltage. It is also necessary to obtain a curtent–voltage relationship for the pump-motor so that the two equations can be solved simultaneously for the operating point.

3. HYDRAULIC SYSTEM AND PUMP-MOTOR

The hydraulic head in a typical hydraulic system consists of a static component and a flow-rate dependent dynamic component. The static head is defined as the vertical distance from the water surface to the point of free discharge. For a pressurized storage system, the equivalent height of water due to the pressure contributes to the static head. The dynamic head is a result of fluid friction. In a PV pumping system, it is desirable to minimize the dynamic head by using a large diameter pipe. Since the head is proportional to the hydraulic power and thus the power required by the pump-motor, a lower dynamic head will reduce the required PV array size. Optimal piping designs will result in 5–20% dynamic head contribution to the total system head at peak-flow conditions. For a small PV pumping system, the total head is taken to be the static head and is assumed to be constant in the following analysis.

The DC motor converts the electrical energy into mechanical energy. The pump converts the mechanical energy into hydraulic energy. Therefore the characteristics of motors and pumps can be represented by current, voltage, head and flow rate. The manufacturer normally provides the head–flow–current–voltage data for the pump-motor combination, not the pump and motor individually. For example, Solarjack (1995) provides flow rate versus head and current versus head tables and graphs of their centrifugal pumps driven by brushless permanent magnet DC motors for different operating voltages.

Instead of using individual motor and pump models, the characteristics of a pump-motor combination are represented by two functions. One is the current–voltage–head function:

$$V=f_1(I,H), \tag{12}$$

where the form of the function is a polynomial in both I and H (possibly with cross terms) and can easily be obtained from linear regression using data supplied by the manufacturer. At any solar radiation, ambient temperature and head, the I–V–H function is used to find the I–V characteristics of the PV pumping system. Equation (2), the I–V relationship of the PV array, and eqn (12), the I–V relationship of the motor-pump for a given head, are solved simultaneously to find the system operating point.

The other motor-pump characteristic relates the fluid flow to the voltage and head as a polynomial similar to eqn (12) and is also found by linear regression.

$$Q=f_2(V,H). \tag{13}$$

This function indirectly relates the flow to environmental conditions because operating voltage depends on the radiation level and temperature. The operating point voltage is used in eqn (13) to find the fluid flow rate at the specified head. Figure 3 shows typical data (open and closed squares) from a manufacturer's catalog and the polynomial curve fits f_1 and f_2 using a 3rd order polynomial with cross terms.

Since it is possible to predict the fluid flow rate at any given environmental condition, a procedure that estimates the long-term performance of a PVPS can be developed and components can be selected for an optimal design.

4. PV ARRAY CONFIGURATION

Given a pump-motor and PV array, the number of PV modules connected in series and parallel is critical to the successful operation of the system. For some PV array configurations, the operating point may be far from the maximum power point of the PV array at all radiation levels and utilization is therefore very low.

As an illustration, the Solarjack submersible brushless DC pump SCSS.7–160 was selected. Figure 4 shows the operating point of the pump-motor powered by 24 Siemens M75 modules at four radiation levels. The curves show that if the configuration of the PV modules is 8 in parallel and 3 in series ($P=8$, $S=3$), the pump will not work at all at a head of 42 m and only very poorly at a head of 28 m. However, if the configuration of the PV modules is changed to

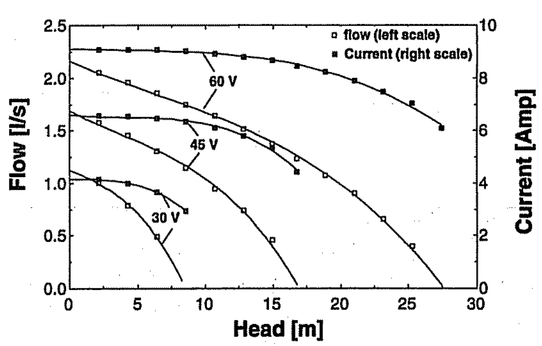

Fig. 3. Flow and current as a function of head and voltage for a typical pump-motor.

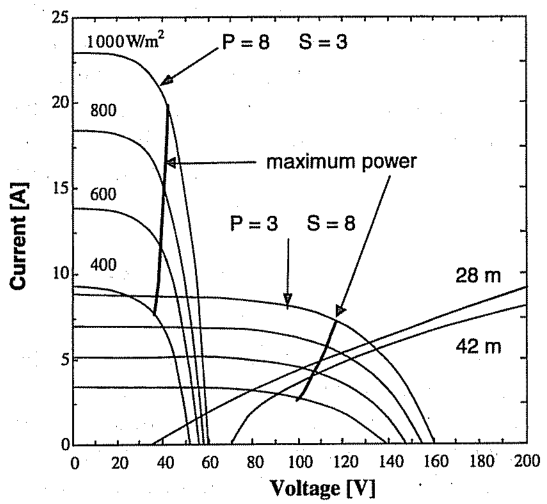

Fig. 4. The operating point of a Solarjack SCS 5.7–160 pump powered by 24 Siemens M75 modules at four radiation levels connected in two different series–parallel configurations.

Table 1. Flow rate at various module configurations: same system as Fig. 4

Radiation (W/m^2)	S=8, P=3 Q[l/s]	Opt. Array Q[l/s]	S, series	P, parallel
100	0.000	0.000	NA	NA
200	0.000	0.014	24	1
300	0.104	0.163	6	4
400	0.243	0.278	6	4
500	0.369	0.369	8	3
600	0.482	0.482	8	3
700	0.582	0.582	8	3
800	0.667	0.667	8	3
900	0.738	0.738	8	3
1000	0.797	0.797	8	3

$P=3$ and $S=8$ then the pump will work relatively well at both 28 and 42 m heads over a wide range of radiation levels.

The objective in optimizing the configuration of a PV array is to maximize the delivered water over a time interval at a given location and known head (the head does not have to be fixed but the change throughout the year must then be specified) by changing the number of PV modules that are connected in series and parallel. The time period investigated here is 1 year but a case can be made for optimizing the delivered water for the worst month. The design method does not change with the time period selected for the optimization. Although an annual assessment is used in this analysis, it has been found that series–parallel optimization at a few radiation levels is often sufficient, at least for an initial screening.

As an illustration consider the system depicted in Fig. 4. For 24 modules there are 8 possible combinations using all 24 modules (i.e. $S=24$, $P=1$; $S=12$, $P=2$;...; $S=1$, $P=24$) and 8 combinations would normally have to be investigated. Table 1 shows the water flow rate with a fixed module configuration of $S=8$ and $P=3$ at ten radiation levels and the optimum module configuration system (selected from the 8) for each radiation level and its associated flow rate. The optimal configuration does not change above a radiation level of 500 W/m^2. For locations with high radiation it is clear that the optimal configuration for annual water pumped will be $S=8$ and $P=3$. For many locations a significant fraction of the monthly pumped water occurs when the radiation on the PV array has a level exceeding 500 W/m^2 and $S=8$, $P=3$ may still be the optimal configuration. In general it would be wise to test other possible configurations, for example $S=6$ and $P=4$ may be the annual optimum for locations with low radiation. However, it is not necessary to test all 8 combinations as only a few combinations have a reasonable chance of being the optimum. Of course, maybe only 20 modules are needed instead of 24 and the possible combinations of 20 modules should be subjected to the same screening process.

5. PV ARRAY TEMPERATURE EFFECTS

The combined PV–motor-pump model described in the preceding sections can estimate the water flow rate at any given temperature and solar radiation. However, the "generated" weather to be discussed in the next section may not correctly account for the correlation between hourly solar radiation and hourly ambient temperatures. Figure 5 shows the fluid flow rate as a function of solar radiation at four different ambient temperatures. As seen in the figure, the pumped water changes little when the ambient temperature changes by 25°C and the effect is pronounced only at radiation levels above 500 W/m^2. Consequently, the monthly average ambient temperature will be used to estimate annual performance. The impact of this assumption is discussed below.

6. WEATHER DATA GENERATOR

In order to simulate the long-term performance of a PV pumping system, it is necessary to have long-term weather data. Such data are not available for some parts of the world,

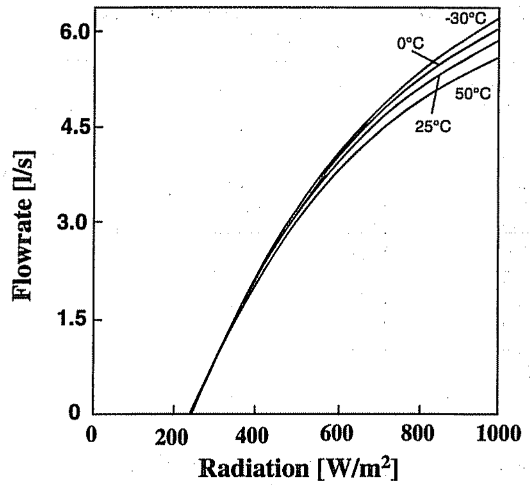

Fig. 5. Effects of temperature and solar radiation on the system flow rate.

particularly in the developing countries. However, PV pumping systems are often considered in areas where hour-by-hour weather data are lacking. A solar radiation data "generator", based on knowledge of the local clearness index, is used in this study to overcome the problem. The relationships and ideas behind the weather generator are all available in Duffie and Beckman (1991). The method is summarized in the following steps:

(1) For each month at the location of interest, estimate the monthly-average clearness index, $\bar{K}_T$. This type of data is often available even if hourly data are not available.
(2) For each month (ie. for each $\bar{K}_T$) use the "generalized distribution of days" to obtain a sequence of daily clearness indices (ie. a set of K_T values that represent the long-term distribution of days). Each month is represented by either one average day or by the number of days in the month. The impact of these two choices is discussed below.
(3) The solar position throughout each day is assumed to be the same within a given month and equal to the solar position for the monthly average day. The hourly fraction of daily total and daily diffuse radiation is then calculated. This procedure leads to the assumption that the hourly variation of solar radiation within each day is symmetric about noon.
(4) The hourly radiation on the surface of a collector can be calculated by using any of the accepted sky radiation models.
(5) Since the monthly average temperature is used for each hour of the month, the monthly weather data can be characterized by the radiation level alone and placed in "radiation bins". Each bin contains the number of hours in the month in which the radiation is, for example, in the range between 500 and 600 W/m^2.

7. THE MONTHLY AND ANNUAL PUMPED WATER

With the PV-motor-pump model and the distribution of solar radiation on the array, it is now possible to calculate the monthly and annual pumped water. For each month and radiation bin, the water flow in one hour, Q_{bin}, is found and multiplied by, n_{bin}, the number of hours in the bin. The calculation is summed over all bins in the month and then over all months (annual).

$$Q_{\text{month}} = \sum_{\text{bin}} n_{\text{bin}} Q_{\text{bin}}, \tag{14}$$

$$Q_{\text{annual}} = \sum_{\text{month}} Q_{\text{month}}. \tag{15}$$

Since the sequence of high and low solar radiation days is not available from the proposed procedure it is not possible to estimate daily water shortages. However, the monthly shortage or excess of pumped water can be calculated knowing the monthly water requirement. If the excess or shortage is consistent throughout the year, then the pumping system can be resized to better match the monthly water requirements.

8. PERFORMANCE ESTIMATES USING TMY DATA

This section presents comparisons between TRNSYS (Klein *et al.*, 1996) simulations using Typical Meteorological Year (TMY) weather data and the results from the proposed method, called UW-PUMP. This comparison is a test of the suitability of the generated weather data for predicting pumped water as both TRNSYS and UW-PUMP use the same PV model and pump-motor model. The comparison is the monthly and annual water output. Six cases were run with each of the two programs: two water heads (28 m and 42 m) and three cities (Albuquerque, New Mexico, Madison, Wisconsin and Seattle, Washington), that cover very different annual radiation statistics.

The components of the PV pumping system are the same as used in Fig. 4 with the PV modules connected eight modules in series, three modules in parallel. The PV array is installed at a tilt angle equal to the latitude and at an azimuth angle of zero. The UW-PUMP program uses generated radiation data and the average monthly temperature whereas TRNSYS uses measured hourly radiation and ambient temperature. The simulations were conducted over a period of 1 year and the results are shown in Fig. 6 for the three cities. The RMS differences between the monthly pumped water from UW-PUMP and TRNSYS range from about 3% in Albuquerque to about 6% in Seattle. The conclusion is that the use of the monthly average temperature and generated solar radiation captures the weather statistics seen by the PV array quite accurately.

Figure 7 shows a comparison of using either one day or a full month of generated weather in the UW-PUMP program. For all three cities, the predicted performance using a full month of generated data are often significantly different from the one day calculations. The most interesting results are for Seattle. One average day cannot adequately predict the monthly performance due to the very nonlinear behavior of a PVPS and the wide range of cloudy and clear days during a month in Seattle. In the months of January, February, November and December the one day calculation provides no pumped water whereas the full month calculation shows a small, but significant, amount of pumped water. An even more disturbing result is in July where the one day calculation estimates about 30% more pumped water than full month calculation. Whenever the $\bar{K}_T$ is very low ($\bar{K}_T$ ranges between 0.26 and 0.35 for these four winter months in Seattle) a one day simulation can be expected to under predict pumped water. In an intermediate range of $\bar{K}_T$, the one day results can be expected to overestimate performance. When $\bar{K}_T$ values are high, as they are in Albuquerque ($\bar{K}_T$ ranges between 0.63 to 0.73 for the entire year), the one day calculation is a reasonable assumption since "every day looks like every other day" and they all look like the average day.

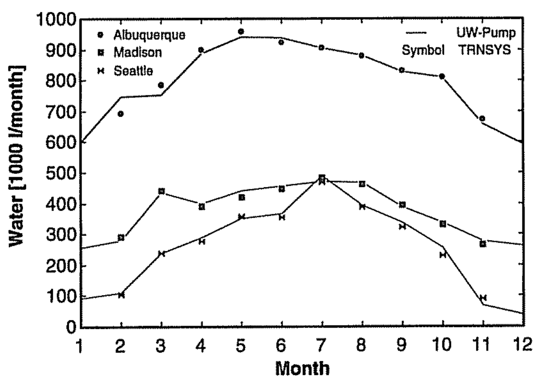

Fig. 6. Monthly pumped water in three cities as calculated by UW–PUMP and TRNSYS.

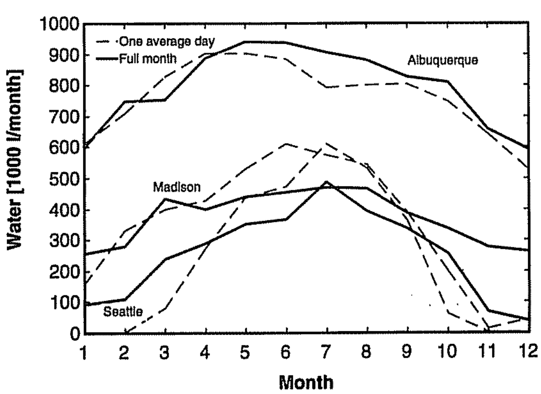

Fig. 7. Monthly pumped water using one average day or a full month of generated days for three cities.

9. CONCLUSIONS

The UW-PUMP program uses a simplified set of hourly weather data derived from average monthly weather data to simulate PV pumping systems. It has been shown to have an annual RMS difference of about 3% (Albuquerque) to 6% (Seattle) compared to the TRNSYS program which uses TMY weather data. The new simplified method can be used in designing and estimating the long-term performance of a PVPS over any monthly or annual period, and over a typical range of US climates. This method can be extended to other applications.

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