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Photovoltaic-Powered Water Pumping-Design, and Implementation: Case Studies in Wyoming

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PHOTOVOLTAIC-POWERED WATER PUMPING - DESIGN, AND IMPLEMENTATION: CASE STUDIES IN WYOMING

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ABSTRACT

A photovoltaic-powered water pumping project comprising of several rural electric cooperatives and their customers is described in detail. A number of remote water pumping installations in the state of Wyoming are currently operating as a result of this project. The design, installation and performance monitoring of these systems are discussed. In general, it can be stated that PV-powered water pumping in this state, has been a cost-effective alternative to distribution line extension or other conventional means of water pumping. Customer satisfaction, in terms of functional adequacy and low maintenance requirements of these systems, is high. The benefit for the utilities concerned, are cost savings and better customer relations.

Keywords: Remote water pumping, photovoltaic power, alternate energy.

1. INTRODUCTION

The five year national photovoltaics program initiated in 1991 targets the utility industry as the primary end-user for photovoltaic (PV) power. Its mission is to make PV a significant part of the national energy mix. Demonstrations of PV projects by utilities in nearly 30 states are working to promote PV as a viable alternative form of electric utility generation [1-11]. The utilization of PV for remote applications is gaining significant importance as awareness of its advantages as a power supply option compared to distribution line extension or other conventional means becomes more widespread. PV systems are already cost-effective for many remote applications, such as water pumping, cathodic protection, line sectionalizing, etc. [12]. Among these applications, remote water pumping for residential water supply, small-scale irrigation or livestock watering, is perhaps the leading candidate for potential widespread acceptance [13-15]. At the present time, there are more than 20,000 PV-powered water pumping installations around the world. The recent successful completion of the K.C. Electric project in Colorado [16] provides valuable lessons on this relatively new field.

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Most rural electric cooperatives (REC) in the western states are responsible for operating and maintaining electrical distribution systems that service primarily remote ranching and farming loads. This distribution system O&M can be costly at times to both the utility and its customers, especially when natural disasters damage the system. Incorporating PV power into their operation can help solve the high costs of serving these small remote loads and at the same time maintain good relations with existing customers. However, for these utilities, reducing the cost of service is only part of the answer: system performance and reliability are two additional factors that are critical. With these goals in sight, five RECs in the state of Wyoming with the help of Sandia National Labs. and the University of Wyoming, initiated a two-year pilot project for installing and monitoring several PV-powered water pumping systems around the state. The major objectives of the project were to:

- Demonstrate to the rural electric cooperatives and their customers, the cost-effective nature of the specific PV application - water pumping.
- Educate the rural electric cooperatives and their customers on procuring such systems on their own.
- Monitor for an extended period of time, the performance and reliability of each sub-system, for example, the motor-pump assembly, the PV modules, the batteries, etc. under different seasonal conditions.
- Monitor customer satisfaction.

This paper describes the project in detail such that similar projects elsewhere can be conceived and brought into reality. Close attention is paid to each phase of the task and successes and failures are pointed out clearly.

The tasks defined for the project were:
- Site selection.
- System design.
- System Installation and testing.
- System performance monitoring.

Descriptions of implementation of the above tasks are given in a later section. The general process of designing a PV-powered water pumping system is described first.

2. SYSTEM DESIGN TO REALITY - A JOINT VENTURE BETWEEN UTILITY AND CUSTOMER

It is becoming apparent that the utility should get involved with its customers in promoting PV power for water pumping in remote locations. Both the utility and the customer benefit from such cooperation. Radial line extensions can become matters of copious investments for both parties and can be easily avoided by seeking the photovoltaic alternative. By working together, they can arrive at a mutually acceptable solution - one where the customer receives the service of water pumping, and the utility retains a satisfied customer without the need for extending the distribution line.

In order to bring about an atmosphere of problem-free cooperation among the parties involved, it is necessary to delegate special responsibilities. These are listed below:

Utility:

- Identify pumping sites using a predefined criteria (described below).
- Complete the pumping specification worksheet (described below) with customer.
- Estimate size and cost of the system.
- Submit Request For Proposals to prospective offerors of PV-powered water pumping systems.

  OR

  Buy system components from vendors. The sub-systems are:
  - PV modules.
  - Motor/pump assembly.
  - Control box, electrical switches, etc.
  - Support rack and pole for PV panel.
  - Float switch.
  - Trackers (optional).
  - Inverter (optional).
  - Batteries (optional).
- Supervise installation and testing.

Customer:

- Complete pumping specification worksheet with the utility representative.
- Review bids from offeror and select suitable system.
- Become cognizant of operation and maintenance of system.

2.1 System Design Guidelines

The systems installed within a utility's service territory will depend on considerations of both technical and economic factors. These considerations, which are described in the following sections, must be optimized in order to provide a cost-effective and reliable water pumping option for the customer.

Technical Factors

The technical factors evaluated for each installation will include the well and pumping characteristics, the solar radiation availability at the site, and the array configuration. In order to design an effective water pumping system, the designer must understand the well, the site terrain, the water requirements, and the storage system details. An understanding of the well requires information regarding the casing diameter, the static and the dynamic water depths. In addition, the water requirements should be known in gallons per day on a seasonal and daily basis. These parameters are used to calculate pumping time, pump size, and power demand on the pump which are in turn used to determine the load current from which the PV system size can be calculated. It is important to know the largest possible water production requirements, so that the system design will account for the worst-case scenario.

Once the sites for locating the PV-powered water pumps are identified, an assessment of the solar radiation at the particular sites is essential. While both flat-plate and concentrator module technologies have matured, the two technologies convert solar radiation to electricity in somewhat different manners. Flat plate cells utilize the global aspects of insolation, i.e., both the direct and diffuse components, while concentrators use only the direct beam component. Naturally, certain sites will be more adaptive to one technology than the other and hence, it becomes a matter of economics to choose the right one.

Most sites around Wyoming are at high elevations, thus receiving radiation with less atmospheric scattering than usual. This increases the possibility of the direct beam radiation reaching the surface rather than the diffuse. Monitoring the direct and diffuse radiation at these sites for a certain period of time will indicate conclusively, the predominance of either component.

An important factor in selecting PV systems is whether the array should be allowed to track the sun continuously. Passive tracking has received much attention in the recent past for such stand-alone applications of PV power. However, continuous tracking, albeit conducive to higher daily collected solar energy, may prove to be a cause of maintenance problems due to severe wind loadings in some locations. The question to be answered is then, does the specific water pumping application require the benefits of a 20-30% increase in the total energy collected through a tracker? In answer to that question, one needs to investigate the daily energy demand, the comparative economics of a tracker versus an increase in the number of fixed solar panels to supply the same energy demand.

The total amount of water required depends on the specific application. If the application is livestock water tank, then the water requirement is found from average consumption of each animal species. In case of irrigation, the requirement is gallons of water per minute needed for a specific land area.

The PV power required is found directly from the total water requirement and the total vertical distance from ground level down to the static water level in the well. Also important is the season during which the well will be used. While irrigation in the state of Wyoming is almost exclusively done is the summer, livestock tanks may need to be operational throughout the year. That means availability of water during the harsh months of winter. This requirement obviously increases the power required from the PV system because of the additional power for heating the tank. In case of water requirement during times of the day when the sun is not shining, a storage option should be considered. Lead-acid batteries are now considered a reliable storage option with a lifetime of over ten years.

Some guidelines are now provided for the technical portion of the design process:

Site Selection Criteria:

- Customer enthusiasm. The utility should work with a customer who feels the need for such a system. The customer must be willing to be educated. A preferred candidate would be one who has requested a line extension.
- Remoteness from the distribution line. The economics of the PV system will be enhanced relative to the cost of the line extension.
- Suitable water source. A well, spring, pond or similar source should be available. The source should be "operational". Sites with currently operating windmills, diesel generators, etc. are examples of suitable water sources. Well test should be done prior to making the final decision.
- Accessibility. Easy access for periodic maintenance is useful.
- Water storage availability. Tank(s) or other devices with adequate capacity should be available.
- Possibility of vandalism. PV modules are expensive items. They have glass encapsulants and are therefore susceptible to breakage due to vandalism. This can be avoided by selecting sites at some distance from busy thoroughfares.
- Weather conditions. At certain locations, mostly isolated range lands at higher elevations, wind can become a factor for either pole-mounted or tracker-mounted PV panels. Also, locations with high probability of cloud cover or even pollution can be detrimental to PV power production.

Pump Sizing Worksheet:

The size of the pump will depend of several factors, such as the water use, the water source, etc. Such information must be studied thoroughly in order to avoid pumping inadequacies after the investment has been made. Table 1 shows a worksheet that can be used for this purpose.

Table 1. Worksheet for pump sizing

WATER USE INFORMATION
Daily Volume of Water Required: Summer: Gallons/Day
Winter: Gallons/Day
Spring/Fall: Gallons/Day
Water Application: (Please circle one) 1. Domestic household use 2. Livestock watering - Number of head: ____ Type of livestock:________________
Type of Storage: (Please circle one) 1. Above ground tank - Size: ________________Gallons 2. Below ground tank - Size: ________________Gallons 3. Pressure tank - Pressure: ________________ psi
WATER SOURCE INFORMATION
Source of Water: (Please circle one) 1. Drilled Well - Well casing diameter __________inches Results based on a recent well test? Yes____No____ 2. Stream or pond 3. Other - Please specify: ________________
Static Water Level: (Distance from ground surface to water when not pumping)__________Feet
Drawdown Level: (Distance water level drops when pumping) ________________Feet
Discharge Head: (Vertical distance water is pumped uphill to tank or distribution)________Feet
Total Head: (Add previous three answers) ________________Feet
Maximum Pumping Rate for Water Source _____Gallons per Minute
ELECTRIC UTILITY INFORMATION
Distance to nearest distribution line: ________feet or ________miles
Line extension cost per mile: $________________
Total Cost for Line Extension: $________________
Customer Cost for Line Extension: $________________

Economic Factors

An economic analysis consists of first determining the capital cost for the PV system and conventional alternative and then calculating the simple or discounted payback periods. Table 2 shows an approximation of capital costs of PV systems and conventional systems found from recent installations [17].

Table 2. Cost approximations of various energy system components

Photovoltaic Systems (With Batteries)	= $20/peak watt
Photovoltaic Systems (Without Batteries)	= $15/peak watt
Photovoltaic Modules (Alone)	= $5-12/peak watt
Diesel Generator Cost	= $500/kilowatt
Battery Storage Cost	= $0.16/watt-hours
Electric Grid Rates	= $0.03-0.13/kWhr
Primary (Non-rechargable) Batteries	= $2/watt-hour

The capital cost of a PV-powered system consists of subsystem costs, such as PV panels, panel structure, pump and motor, batteries (if required), inverter or power conditioning unit (if ac motors are used), system controller and miscellaneous items such as wiring, site preparation, computer housing, etc.

At the present time, PV power systems for large scale power generation are plagued by high initial capital cost. However, for remote applications, the initial capital cost of conventional energy sources should also reflect all the associated capital costs, such as excavation, wiring, and transformer costs commonly associated with line extension.

The combination of costs, or in other words, the life cycle cost is the true measure of cost-effectiveness and should be used as the basis for selecting a specific power system for water pumping. A payback period is simply a calculation of how long it would take to "pay for" the new equipment taking into account the savings to be realized. The "simple" payback period does not take into account the time value of money; the "discounted" payback period does. Simple payback is calculated according to the following formula:

$$\frac{\text{Capital cost of PV system - Capital cost of conventional system}}{\text{First year O\&M cost of conventional system - First year O\&M cost of PV system}}$$

The total cost of the PV system is related to the amount of water that is to be pumped. Table A1 of the appendix shows this relationship, which can be utilized to arrive at an approximate cost of the system.

2.2 Installing and Testing the System

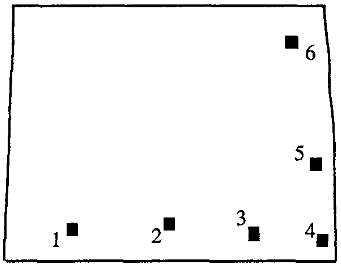
The system should be installed to optimize the use of the solar irradiance available at the site. All appropriate NEC code should be followed for installing the system. Suggested practices for PV system installation that follow the NEC code, have recently been compiled [18].

Upon completion of the installation, the system should be tested for functionality. Testing should include:

- An "instantaneous" system test (e.g., 5 minutes) to assess the power supply performance. Measure solar irradiance, system power, V_{OC}, I_{SC}, module temperature, and water output during this time.
- A "one hour" system test to determine the nominal system pumping effectiveness. Measure solar irradiance periodically (e.g., 15 minute intervals) and water output for the one hour period.
- Testing of automatic and manual control functions.
- Measurement of battery output and cell(s) capacity if batteries are used.

3. WYOMING PILOT STUDY RESULTS

Five electric cooperatives in the state of Wyoming expressed their interest in participating in the pilot project after the project initiative was announced from the University of Wyoming (UW). The service territories of these utilities as well as the location of UW are indicated on the map of the state of Wyoming drawn in Fig. 1.



1 - Bridger Valley Electric Assoc. Mountain View, WY
2 - Carbon Power & Light Saratoga, WY
3 - University of Wyoming Laramie, WY
4 - Rural Electric Co. Pine Bluffs, WY
5 - Wyrulec Co. Lingle, WY
6 - Tri-County Electric Assoc. Sundance, WY

Fig. 1 Map of Wyoming Showing Geographical Location of Each Participant.

3.1 Candidate Site Selection

During a kickoff meeting, all five participants were asked to identify potential sites according to a given set of criteria, for installing the PV-powered water pumping systems. Some weeks later, the information provided by each utility was compiled and seven specific sites were selected. The most common reasons for such selection were:

- Customer had requested a line extension.
- Customer was enthusiastic in learning about the alternative technology.
- Multiple pumping sites located at the same ranch. A portable trailer-mounted PV system could be experimented with.
- Ease of access from utility headquarters. (The utility representative needs to make frequent visits).
- High visibility. This was important because of the demonstrative nature of the project.

The sites ranged from flat range lands to rolling hills vegetated with sagebrush and native grasses. All locations are at high elevations, ranging between 4,500 to 8,200 feet above sea level. The wind can be a severe impediment to tall structures in such locations. Of course, most locations in Wyoming are known for their harsh winters and heavy snowfall.

3.2 System Selection

A total of six systems were selected through competitive bidding from system vendors. A separate system which was to be installed at the UW site was donated for the project by Apollo Energy Systems of Navasota, Texas. System descriptions of the seven systems are shown in Table 3. Figures 2 and 3 show the Rural Electric Association PV system during testing and the Tri-County PV system during installation respectively.

Table 3. System Descriptions

	PV-POWERED WATER PUMPING SYSTEMS						
	Carbon #1	Carbon #2	Rural	Bridger	Tri-County	Wyrulec	UW
Site Description							
Present power supply	Gas generator	Gas generator	Windmill	Diesel generator	None	Windmill	AC line
End Use	Livestock	Livestock	Livestock	Livestock	Livestock	Livestock	Livestock
Total Head (feet)	298	22	140	27	140	WI: 95 SU: 135	10
Storage type and	Above ground (3)	Above ground	Above ground	Excavated dirt pond	Above ground	Above ground	Above ground
size (gals)	50,000	1,000	4,000	10,000	1,400	15,000 7,500	
Elevation (feet)	8,200	7,200	5,100	7,220	4,750	4,500	7,200
Pump Description							
Pump type	Centri-submersible	Centri-submersible	Centri-submersible	Centri-submersible	Submersible-diaphragm	Centri-submersible	Centri-submersible
Model	N/A	211008DM	211011DK	211008DM	SDS-D-128	21108DK	N/A
Motor type	ac	Brushless dc	Brushless dc	Brushless dc	Brushed dc	Brushless dc	Brushed dc
Manufacturer	Grundfos	A.Y. MacDonald	A.Y. MacDonald	A.Y. MacDonald	Solarjack	A.Y. MacDonald	Apollo
PV Array Description							
Module Rating (watts)	60	56	63	56	56	60	60
Manufacturer	Solarex	Solarex	Kyocera	Solarex	Solarex	Solarex	Solarex
No. of Modules	16	6	9	4	2	10	2
Total rated power (watts)	960	336	576	224	112	600	120
Nominal voltage (V)	120 (2)	36	61	24	24	60	24
Mounting Configuration							
Type	1-axis tracking	Fixed	1-axis tracking	Fixed	1-axis tracking	Fixed	Fixed
Manufacturer	Zomeworks	N/A	Zomeworks	N/A	Zomeworks	N/A	N/A
System Description							
Installation Date	May-91	Nov-91	Oct. 10, 1991	Nov. 12, 1991	Oct. 24, 1991	Nov. 22, 1991	Sept. 22, 1991
Design flow rate (gals/day)	1,500	7,500	2,250	2,500	485	2,500	2,520
Seasonal use	Su, Sp, Fa	Year-round	Su	Su, Sp, Fa	Su, Sp, Fa	Wi, Su (1)	Sp, Wi, Fa
Battery capacity	N/A	N/A	N/A	N/A	N/A	N/A	220
Installed cost ($)	14,000	8,928	6,116	5,644	3,439	8,697	3,850
Utility line Extension							
Distance (miles)	3.5	0.75	1	1	1.33	1.5	N/A
Cost ($)	50,000	9,000	7,500	9,000	13,000	11,457	N/A

(1) Portable trailer-mounted system (2) AC motor is powered through inverter (3) Uses gravity-feed to smaller tanks

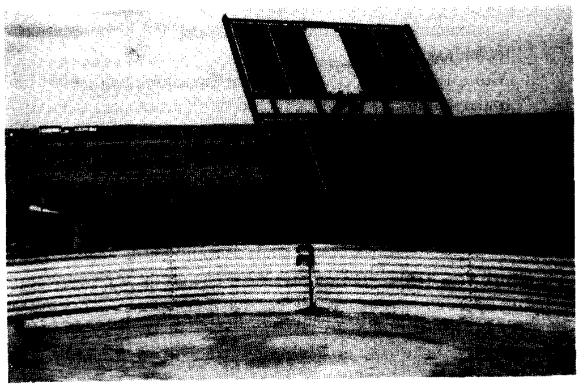


Fig. 2 The system at Pine Bluffs, WY. The old windmill can be seen in the background.

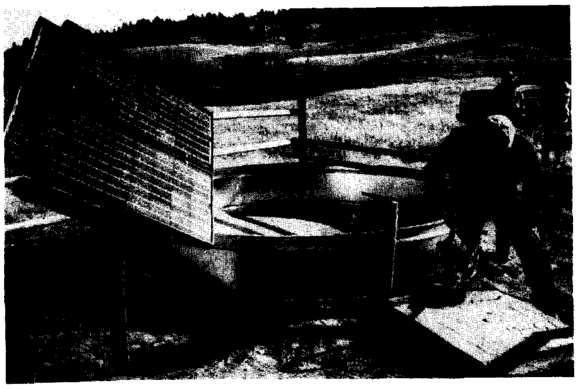


Fig. 3. Installation and testing of the system at Sundance, WY.

Six out of the seven systems are direct-coupled or panel-direct systems operating without the aid of a battery. The other system, located in Laramie, uses a battery to operate the motor. The choice of this alternative form of operation was dictated by our desire to learn about specific characteristics of such a system which included the ability of batteries to withstand sub-freezing temperatures, a very common occurrence in the state during the winter. Typically in water pumping applications, the function of the battery is not so much for storage as for its suitability for large volume pumping in lesser time. Of course, the cost of the battery is an additional cost item. However, it must must be weighed along with other criteria. The following points will highlight some of the differences of a panel-direct versus a battery-operated system.

- A panel-direct system is normally meant to be used for low volume, low head pumping use.
- A panel-direct system requires larger number of PV modules to generate enough amperage to drive the motor.
- Most often, a panel-direct system will require a tracking system for extending the operating time so it can pump similar amount of water.
- Inadequate sunlight during partly cloudy days can prevent the motor from operating in panel-direct systems.

3.3 Performance and Reliability Monitoring

One of the goals of the project was to collect data on the performance and reliability of PV-powered water pumping systems. The seven systems installed in Wyoming are being monitored closely, both by utility representatives and customers. The performance and reliability aspects of these systems to date is summarized individually under each utility participant.

<u>Carbon Power - System #1</u>

Performance Summary:

System type:	Centrifugal-Submersible.
Operating Period:	Aug. '91 - Oct. '91, Jun. '92.
Owner feedback:	"Satisfactory".

Reliability Summary

Failures:	2
Failure Description:	Tracker problems. Shock absorber.
Failure Cause:	High wind loading.
Repair:	Shock absorber repaired on both occasions.
Comments:	The system was re-started in June 1992. However, it was shutdown almost immediately due to pipeline problems. The pipeline had to be repaired.

<u>Carbon Power - System #2</u>

Performance Summary:

System type:	Centrifugal-Submersible.
Operating Period:	Nov. '91 - Apr. '92
Owner feedback:	"Very Satisfied". System pumped 16,425 gals in 41 days of testing.

Reliability Summary

Failures:	1
Failure Description:	Pump clogging due to sand from well.
Failure Cause:	Sand content in well.
Repair:	Pump was cleaned and filter re-installed.
Comments:	System operation during summer was delayed because the summer well had to be "blown".

<u>Rural Electric</u>

Performance Summary:

System type:	Centrifugal-Submersible.
Operating Period:	Oct, '91.

Reliability Summary

Failures:	1
Failure Description:	Well collapsed.
Failure Cause:	Poor well selection.
Repair:	New well was being drilled.
Comments:	System operated as expected during installation.

<u>Bridger Valley</u>

Performance Summary:

System type:	Centrifugal-Submersible.
Operating Period:	May. '92 - Aug. '92
Owner feedback:	"Very Satisfied". System pumped 51,800 gals through June 3rd. Averages 2,200 - 2,300 gpd in the summer.

Reliability Summary

Failures:	None
Comments:	Modules needed periodic cleaning because of accumulation of dust and bird dropping.

Tri-County Electric

Performance Summary:

System type:	Submersible-Diaphragm.
Operating Period:	May '92 - Aug. '92
Owner feedback:	Feels not enough water is available for the livestock. Wants to install batteries for 24 hour operation.

Reliability Summary

Failures:	None.
Comments:	Solarjack may replace pump because of lower flow rate than designed.

Wyrulec Company

Performance Summary:

System type:	Centrifugal-Submersible.
Operating Period:	Nov. '91 - Apr. '92, May '92 - Aug. '92.
Owner feedback:	"Satisfied". System is pumping 2,800 gpd on the average during the summer.

Reliability Summary

Failures:	1
Failure Description:	Pump clogging due to sand from well.
Failure Cause:	Sand content in well.
Repair:	Pump was cleaned and filter re-installed.
Comments:	Golf-ball sized hail was reported at the site. No noticeable damage to the modules was observed.

UW

Performance Summary:

System type:	Centrifugal-Submersible.
Operating Period:	Feb. '92 - May '92
Owner feedback:	"Very Satisfied".

Reliability Summary

Failures:	1
Failure Description:	Electric float switch froze.
Failure Cause:	Freezing temperatures.
Repair:	Switch was replaced by a ball float.

4. CONCLUSIONS

This paper takes a comprehensive look at PV-powered water pumping systems from conceptualization to design and implementation. Remote water pumping is now a cost-effective application of PV power because of the high initial cost of distribution line extension arising from such capital costs as as excavation, wiring, and transformer costs.

The paper also describes a pilot project initiated in the state of Wyoming in 1991. The overall importance and timeliness of this project for the U.S. in general and Wyoming in particular, is underscored by the composition of the various parties for this project: (1) Five Wyoming Rural Electric Associations each contributing technical man-power and site location; (2) Sandia National Laboratories, having the premier national laboratory for photovoltaic applications research; (3) NEOS Corporation which has a multi-year, competitively-won contract to provide technical assistance to the Western Area Power Administration's Conservation and Renewable Energy Program covering thirteen western states including, Wyoming; and (4) the University of Wyoming. This cooperative effort provided the project a unique perspective from academic insight, balanced by industry realism and practicality.

Several key questions are being answered through this on-going project. These are:

- Relative advantages of panel-direct versus battery-included systems.
- Specific problems of sub-system operation at sub-zero temperatures.
- Relative performances of four different pump variety: the Grundfos centrifugal submersible ac pump, the Solarjack submersible diaphragm dc pump, the A.Y. MacDonald centrifugal submersible dc pump and the Apollo staged impeller, centrifugal submersible dc pump.

More specific system operation data will be made available after the systems have been in operation for at least two years. For the present time, it can be concluded that photovoltaic power is a cost-effective alternative for remote water pumping judging from the adequacy of performance of the installed systems and customer satisfaction. Most of the reliability problems that have occurred to date have been due to events unrelated to the PV system, e.g. well collapse and high wind gusts.

This demonstration project has resulted in an increased awareness of PV-powered water pumping technology among both electric cooperatives and ranchers/farmers around the state. A number of cooperatives and their customers have inquired about the systems and the possibility of acquiring such systems for themselves. Some have already installed similar systems at their sites, while others are in the process of replacing their existing power sources with PV systems.

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APPENDIX

Table A1. PV Water Pumping System Size and Cost Estimation Chart. (1)

PRICE FOR SYSTEM (3)

PEAK WATTS FOR SYSTEM (3)

GALLONS PER DAY (3)

Cheyenne, Wyoming Summer	Spr/Fall	Winter										
36,000	27,000	22,500	14,000 1,100	16,000 1,400	(2) (2)	(2) (2)	(2) (2)	(2) (2)	(2) (2)	(2) (2)	(2) (2)	(2) (2)
24,000	18,000	15,000	$9,400 630	$12,000 880	$18,000 1,600	$23,000 2,100	(2) (2)	(2) (2)	(2) (2)	(2) (2)	(2) (2)	(2) (2)
14,400	10,800	9,000	$8,600 440	$10,000 700	$14,000 1,100	$16,000 1,300	$20,000 1,800	$24,000 2,300	(2) (2)	(2) (2)	(2) (2)	(2) (2)
9,600	7,200	6,000	$7,400 330	$8,800 560	$9,900 670	$14,000 1,100	$15,000 1,200	$16,000 1,400	$21,000 1,900	(2) (2)	(2) (2)	(2) (2)
7,200	5,400	4,500	$7,200 310	$8,600 440	$8,500 520	$11,000 820	$12,000 890	$15,000 1,200	$16,000 1,400	$20,000 1,800	(2) (2)	(2) (2)
4,800	3,600	3,000	$6,800 280	$7,200 310	$7,900 370	$9,800 660	$10,000 710	$12,000 900	$14,000 1,100	$16,000 1,400	$20,000 1,800	(2) (2)
3,840	2,880	2,400	$6,500 250	$6,800 280	$7,100 310	$8,300 490	$9,300 610	$11,000 830	$12,000 950	$13,000 1,100	$16,000 1,400	$23,000 2,100
2,880	2,160	1,800	$2,400 120	$2,900 160	$6,500 250	$7,600 330	$8,300 500	$9,400 620	$10,000 710	$12,000 970	$15,000 1,200	$17,000 1,500
1,920	1,440	1,200	$2,200 100	$2,500 130	$2,500 130	$2,600 140	$6,300 310	$6,300 340	$9,000 580	$11,000 830	$13,000 980	$14,000 1,100
1,440	1,080	900	$1,800 80	$2,300 110	$2,300 110	$2,500 130	$2,700 150	$5,700 290	$6,900 400	$7,800 550	$11,000 820	$13,000 980
960	720	600	$1,700 60	$2,000 100	$2,000 100	$2,100 110	2,200 120	$5,000 230	$5,500 280	$6,900 460	$9,600 640	$11,000 810
480	360	300	$1,300 30	$1,800 70	$1,800 70	$1,900 80	$2,000 90	$2,100 100	$4,900 2209	$5,500 270	$6,100 330	$7,100 460
240	180	150	$1,300 30	$1,400 40	$1,400 40	$1,400 40	$1,500 50	$1,700 60	$1,700 60	$1,900 80	$1,900 80	$2,000 90
			20	30	50	75	100	125	150	200	250	300

PUMPING HEAD (Feet)

(1) This chart gives a rough first estimate of the size and cost of PV pumping systems excluding installation. These estimates are based on a sampling of available pumps and PV system components.

(2) No pumps identified for this size application.

(3) The costs, peak watts and water delivery (gallons per day) are based on a direct-coupled system (no batteries) that includes a single axis tracker set for latitude tilt.

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