PERFORMANCE OF A SOLAR PUMP SYSTEM FOR SUBIRRIGATING CORN THROUGH A SUBSURFACE DRAINAGE SYSTEM

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Abstract:
A solar powered pumping system was assembled and operated to supply subirrigation water for 15.4 acres of corn in Cape Girardeau County, Missouri. Water was applied through a subsurface drainage system and utilized a water level control device to manage the water depth in the soil profile. The solar pump operated at or above its predicted performance throughout the test. A severe drought resulted in the landowner providing additional subirrigation water throughout the season. Corn grain yield increased 35% with the subirrigation system compared to a non-subirrigated portion of the field. The DRAINMOD computer program was used to calculate relative corn yields without controlled drainage, with controlled drainage, and varying levels of subirrigation. The solar pump system was more economical than a conventional electric system at this location.

Introduction:
Integrated water management systems offer agricultural producers the opportunity to improve water quality by controlling subsurface drainage water flow during the winter months (Frankenberger et al., 2006) while improving soil and crop conditions through improved drainage and in some cases subsurface irrigation (USDA 2001). Water table management systems that include subsurface irrigation may make the systems more economically viable compared to those that provide controlled drainage in areas that are prone to drought conditions. Integrated water management systems may be remotely located with limited options for accessing water for subsurface irrigation. Some producers have attempted to add water to their water table management system using portable gasoline powered pumps. In 2006, a group of farmers expressed interest in exploring solar electricity as an alternative for powering subirrigation water supply systems in Missouri. The objectives of this project were to 1) design a solar pump system to provide water for an integrated water management system, 2) determine the feasibility of using the solar generator to operate other farm or home equipment or generating power for sale to electric companies, 3) evaluate crop response using drainage plus subirrigation compared to a non-drained, non-irrigated portion of the field, and 4) determine if solar pumping systems are an economically feasible alternative to conventional electric systems.

Materials and methods:
Solar Pump System Design. The solar pump system was designed and field tested near Gordonville, MO (37.2784 N, 89.6741 W). The system utilized readily available solar pumping components (Figure 1). In an effort to minimize costs, it was decided that the system would be designed so that the pump would use electricity as it was generated. No battery storage was included in the design due to additional cost and complexity of the system. The soil profile was used to store water for future plant use. The water holding capacity of the soil allowed over 21 days of irrigation water storage in the soil profile measured as a 50% depletion of the available

water capacity of the upper 60 in. in the soil profile with an average crop uptake of 0.30 in./day (Dalton, 2003).

The system was trailer mounted to provide the capability for generating farmstead electricity during non-subirrigation periods. The subirrigation water source was an adjacent perennial stream. The system was designed to lift water approximately 14 ft from the stream to the field with 150 ft of collapsible 2 in. hose to transfer water from the pump to the field. The water hose added approximately 22 ft of effective head or resistance to the system. Altogether the system pumped against 36 ft (15.6 psi) of back pressure.

Figure 1. Landowner, Mark Wessell, with the 2007 solar pump system. (Kit Doyle photo)

There were few direct current (DC) solar pumps available that pumped high volumes of water at the initiation of this project. The largest available pump (Grundfos 75 SQF-3, Bjerringbro, Denmark) at the time was selected with 56 gpm of flow at 36 ft of head pressure with a 1200 W solar array. The pump motor utilized DC power from 30 to 300 V. An interface control box (Grundfos SQF IO100, Bjerringbro, Denmark) was used as the control switch for the system. Solar panels (Evergreen EC-120-GL, Marlboro, MA) rated at 120 W were selected for the panel array. Individual panels provided electricity at 19.6 V and 6.12 A which required 10 panels wired in series to generate an output of 196 V and 6.12 A. A portable trailer and solar panel bracket system was locally designed and fabricated (Mouser Steel, Patton, MO).

Feasibility. During the non-crop growing season, the system was used to determine the feasibility of using the solar panels to operate other farm or home equipment or to generate power for sale to electric companies. One of the goals of the project was to wire the solar system into the farmstead grid. Wiring into the grid would enable the system to supply electricity which may reduce the farmstead's total electric consumption. A converter (Sunny Boy SWR1100U, Grass Valley, CA) was selected to convert solar electricity from DC to 220 V AC.

Missouri law requires utilities to accept electricity into the grid (MDNR, 2008). However, the local utility required an initial fee of $100, a monthly maintenance fee of $6, and required additional meter installation of $200. The utility would purchase electricity at a rate of 1.55 cents/kWh during the non-irrigation months. Since the cost of the fees was expected to be in excess of the value of the solar electricity provided during the non-irrigation season, this option was forgone in 2007. The subirrigation test site was moved to a location with supplemental pumping capabilities to assist the solar pump system if needed. This allowed a comparison between the solar and gasoline powered pumping system.

Economic Analysis. The solar pump system costs including the trailer and other associated costs are summarized in Table 1.

Table 1. Solar pump component costs.

Solar pump components	Cost
	$
Evergreen Solar Modules, 10 panels x 120 W/panel	5940
Grundfos 75 SQF-3 Pump	1781
Grundfos SQF IO100 Switch Box	134
Misc. splices, plates, nuts	88
Shipping	508
Two-axle trailer, 20 ft, with solar panel frame and assembly	2965
Electrician for assembly and safety review	187
Total	11,603

Integrated Water Management Site. The solar pump water was distributed throughout the field by an existing subsurface drainage system designed (USDA-NRCS, Jackson, MO) with subirrigation capabilities. The system was installed in 2006 with laterals on 30 ft centers (Figure 2). The soil was a Wilbur (mixed, nonacid, mesic Aquic Udifluvents) silt loam. The drainage/subirrigation system was designed with a drainage coefficient of 0.375 in./day in drainage mode and to supply 0.35 in./day in subirrigation mode. Laterals were 4 in. micro-slit perforated corrugated tubing (Valley Tile, Sullivan, IN) buried 36 in. below the previously land leveled soil surface. Subsurface water level control utilized a 48 in. in-line stoplog box (AgriDrain, Adair, IA). Subirrigation water was added to the system through a riser at the northern end of the field. The entire field was 16.2 acres with the subirrigation system covering 15.4 acres. Daily water pumping rate, peak observed flow rate, and the impact of solar panel orientation on water flow rate were determined. Additional evaluations compared the solar pump system to a gas powered pump system.

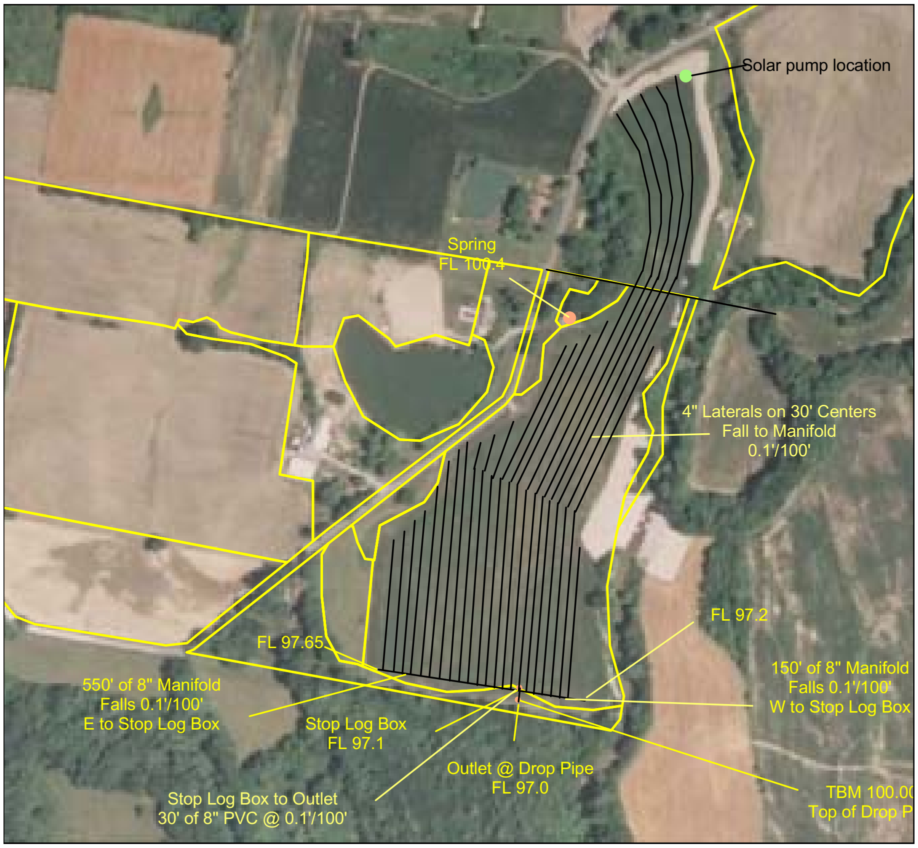

Figure 2. Aerial view of corn field test site showing drainage/subirrigation laterals and location of the solar pump.

Results and discussion:

Water Management. Rainfall was 7.1 in. less than average and evapotranspiration (ET) was 2.1 in. greater than average for the site (Table 2). However, with these drought conditions the crop water needs were met by pumping 14.8 in. equivalent of water (Figure 3). The field was estimated at 75% field capacity (personal observation) at the initiation of subirrigation and was designed not to allow the field to fall below 50% of field capacity. This resulted in an estimated 3.2 inches of stored water in the soil for the crop. In a more typical year, higher rainfall in May would have provided greater water storage in the soil profile and delayed the start date for subirrigation.

Table 2. Rainfall and evapotranspiration (ET) in 2007 (Missouri Historical Agricultural Weather Database, 2007).

Month	Rainfall for 2007	Average rainfall	2007 ET	Average ET
	in.	in.	in.	in.
June	1.6	4.1	8.2	8.1
July	2.1	3.8	9.3	8.6
August	0.4	3.3	3.2	1.9
Total	4.1	11.2	20.7	18.6

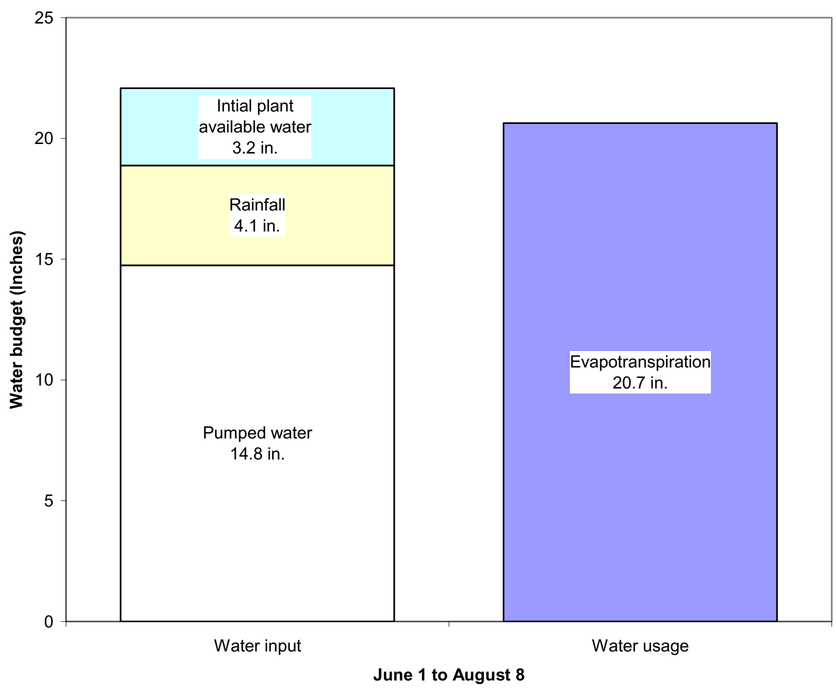

Figure 3. Water budget for the subirrigation system from 1 June to 8 August 2007.

Conventional Pump System. Subirrigation was initiated on 1 June due to the onset of an early drought. A gasoline powered pump was used initially since the solar system was not completely assembled. The gasoline pump was operated 24 h/d from 1 June to 20 June whenever there was little stream turbidity. The water source is a stream that is often turbid for 3 to 4 d following rainfall. Subirrigators are reluctant to pump turbid water due to concerns about silt possibly clogging the tubing. The water level in the water control box was used as a guide for subirrigation. It was determined that the gasoline pump was barely keeping up with crop demand. The system typically maintained a water table about 18 in. below ground surface at the water level control structure. The top stoplog was set about 12 in. below ground surface at the box. The water level did not exceed the top stoplog and spill excess water during the growing season, even after rainfall events (personal observation).

Solar Pump System. The solar pump began operating on 20 June 2007 and pumped until subirrigation was discontinued on 8 August. The gasoline pump operation was reduced to an average of 12 h/d from 20 June through 8 August since the solar pump system operated during the day. Both pumps were shut down on days with unacceptable stream turbidity. The stoplogs inside the water control structure were set to maintain a water level 12 in. below ground surface at the south end of the field, 23 in. below ground surface at the field midpoint, and 34 in. below ground surface at the northern end of the field (Figure 2). The subirrigation laterals were 36 in. below field elevation; therefore, subirrigation water barely made it to the upper end of the field. The system was originally designed with an emphasis on managed drainage to reduce nitrate-N loss during the winter months (Frankenberger et al., 2006) with subirrigation being a secondary consideration.

Table 3. Total gallons pumped by solar pump, and observations for selected dates.

Day	Gallons pumped	Observations
21 June	31,190	Mostly clear. First full day of pumping.
29 June	24,680	Overcast entire day.
30 June	25,235	30 June and 1 July were overcast.
1 July	25,235	Pumping rates for 30 June and 1 July are averaged.
2 July	40,600	Mostly clear. Panels were set for manual tracking.
3 July	42,250	Mostly clear. Panels were set for manual tracking.

The system was monitored daily from 21 June until 2 July except for 22 June through 28 June, when stream turbidity prevented pumping (Table 3). During this period, the solar panel was set flat from 21 June through 1 July which was optimal for mid-day operation. Typical pumping rates ranged from 24,680 gallons/d on 29 June, with overcast skies most of the day, to 31,190 gallons/d on 21 June which was clear most of the day. Peak observed flow rate was 77 gpm at 1400 h on 20 June. It became apparent that total gallons pumped per day could be significantly influenced by orienting the solar panels with the sun. An informal test was performed on 2 July to evaluate the effect of changing the panel orientation on pumping rate. A more controlled test was performed on 3 July whereby the array was oriented 45 degrees to the east at dawn, set flat at 1000 h, and set 45 degrees to the west at 1520 h. The weather was mostly clear for the test. The system pumped 42,250 g/d which was a 35% increase in performance from the peak output observed on 21 June, which was a similar weather day. After the 3 July test, the system was primarily managed by the landowner. The solar panels were manually oriented to the sun three times daily nearly every day in July to maximize the solar pump output and minimize gasoline consumption. Subirrigation was terminated on 8 August at the corn field. The system was moved to a soybean field and pumped continuously with the panels set flat until 31 August. The pump operated continuously from 8 August to 31 August and averaged 27,860 g/d. Subirrigation pumping was terminated on 31 August.

Records for the solar and conventional pump system were consolidated for the corn field site. The corn field received an equivalent of 4.1 gpm/acre on a continuous basis from 1 June to 8 August after pro-rating for days with no pumping due to creek water turbidity and the calculated net average flow rate for combined solar and gasoline pumps. This was equivalent to 0.21 in. of subirrigation water per day, or 14.75 in. for the 68 d subirrigation period. If the solar system alone had pumped daily from a well water source, thereby eliminating pumping disruptions due to creek water turbidity, and had the solar panels remained in a flat condition, we estimate it would have pumped approximately 30,000 gal/d. This would have been equivalent to 1.4 gpm/acre at a 24 h/d rate throughout the season.

Crop Yield. The corn crop was harvested on 1 September. The subirrigated portion of the field averaged approximately 210 bu/acre (personal observation). The southeast corner of the field (Figure 2) did not have drainage/subirrigation installed because drainage was the primary concern during system design and that area already had adequate drainage. The non-subirrigated portion of the field averaged 155 bu/acre and a distinct line was present where there was no subirrigation (personal observation).

Predicting Yield Using the DRAINMOD Computer Program. The DRAINMOD (Skaggs, 1999) computer program was used to determine optimum system design from an economic standpoint for Wilbur and Wakeland (mixed, nonacid, mesic Aeric, Fluvaquents) silt loam soils (Table 4). These soils are primarily found in northeast and southeast Missouri (MDSS, 2008a; MDSS, 2008b). Computer output was in terms of annual relative yield, which is the yield that would be expected in a year with ideal growing conditions. An optimal year would have an annual relative yield of 100%. For the model, the optimal predicted relative yield was 275 bu/acre. The time period from 1961 through 1996 was analyzed utilizing weather data from the Cape Girardeau, MO airport (37.2248 N, 89.5709 W). The use of relative annual yield simplifies data analysis since corn yields continue to rise on a long term basis.

Table 4. A comparison of annual relative yields for subsurface drain tile spacings and subirrigation supply rates for a Wilbur and Wakeland soil.

Drain tile spacing	Subirrigation water supply	Annual relative yield	Yield increase over the non-drained control	Yield increase over the non-drained control	Annualized system cost	Installation cost[a]
Ft	g/min/ac	%	%	Bu	$	$/Bu
Non-drained	0	40.3	0	0	0	0
30	0	59.5	19.2	53	84.78[b]	1.60
45	0	56.7	16.4	45	64.53	1.43
60	0	52.0	11.7	32	54.40	1.70
30	1.50	78.3	38.0	104	104.78	1.01
45	1.50	73.5	33.2	91	84.53	0.92
60	1.50	68.8	28.5	78	74.40	0.95
30	2.25	83.7	43.4	119	114.78	0.96
45	2.25	78.5	38.2	105	94.53	0.90
60	2.25	70.2	29.9	82	84.40	1.03
30	3.00	84.1	43.8	120	124.78	1.04
45	3.00	79.3	39.0	107	104.53	0.98
60	3.00	73.4	33.1	91	94.40	1.04

[a]The installation cost ($/bu) does not indicate the point of maximum economic return. These results identify system cost and expected yield increase. Additional analysis is needed to identify the maximum economic return. These results identify economic inflection points that need additional analysis.
[b]Annual costs were determined using the actual cost from recently installed systems. Interest was estimated at 6% with a 20 year lifespan. Cost of the drainage system on 30 ft lateral spacings was $696/acre for 4 in. laterals, $46/acre for the main, $60/acre for 10% of the water level control structure, $20/acre for outlet section, taps, and tees for a total of $822/acre and $972/acre with land leveling. Subirrigation pumping cost was estimated at $20/ac/year at 1.5 gpm/acre, $30/acre/year at 2.25 gpm/acre, and $40/acre/year at 3.0 gpm/acre.

DRAINMOD utilizes water stress resulting from over-saturation, under-saturation, and delayed planting as yield reduction factors to determine yield potential. Other factors such as fertility, tillage, and hybrid are not included. DRAINMOD has effectively predicted water supply and drain tile spacings for Wilbur and Wakeland soils. The most economical design for these soils was a 45 ft spacing with 2.25 gpm/acre subirrigation water supply. The producer selected 2.25 gpm/acre with a 30 ft spacing at this site for water supply flexibility.

Solar System Cost versus Conventional Cost. The 2007 solar pumping system cost totaled $11,603 (Table 1). Solar panel prices have decreased significantly since panels were purchased for the 2007 test and are projected to continue to decrease. A new solar pump model was introduced in 2008 and has a 1600 W rating compared to the 1200 W pump used in this project. The 1600 W pump has approximately 33% greater pumping capability than the 1200 W pump. Area farmers have expressed interest in constructing 1600 W systems with an estimated cost of $10,900 per system. (Table 8)

Table 5. Component cost of a 1600 W solar pumping system in fall, 2007.

1600 W solar pumping system components	Cost
	$
12 solar panels (approximately 130 W each)	6,300
Grundfos 60 SWF-3 Pump	1,600
Grundfos SQF IO100 Switch Box	100
Misc. splices, plates, nuts	200
Shipping for above	500
Two-axle trailer, 18 ft, standard trailer	900
Removable solar panel mount assembly	1,000
System assembly	300
Total system cost	10,900

The 1600 W system has a 33% increase in wattage and theoretically a 33% increase in pumping capability. However, we expect that future systems will be installed with groundwater wells as the water source. Total lift may range from 40 to 50 ft based on a few wells that have been dug in the area to date which is greater than the 36 ft of vertical lift in the 2007 test. A 1600 W system should provide sufficient subirrigation water for a 15 to 20 acre corn field using current recommendations of a minimum 1.5 gpm/acre subirrigation rate.

A preliminary evaluation of Federal and USDA renewable energy programs indicate that solar pump systems may be eligible for a 10% Federal tax credit and a 30% USDA renewable energy grant. This adjusts the landowners' cost to be approximately $6,540 for the 1600 W system.

The 2007 test site landowner, Mark Wessell, is currently investigating options for providing permanent subirrigation water to the test field that requires less daily labor than his existing portable gasoline pump. His current gasoline pump system draws water from a perennial stream and requires manual pump shutdown if stream turbidity is noted after rainfall events. There are concerns that numerous pumps withdrawing water from Missouri streams could affect stream quality. The landowner has investigated installing an electric pump in a permanent well. Electric utility poles are currently in this field. His local utility charges $3,000 for an initial electrical drop to the pump, plus a charge of about $25/month whether electricity is used or not. It was estimated that a conventional electric pump would use so little electricity that the monthly bill would likely be $25/month or less even during subirrigation months. The $25/month charge is equivalent to $300/year. Using a system lifetime of 20 years and using a 6% interest discount rate, a $300/year charge is equivalent to an initial cost of $3,440. The lifetime and initial cost of a conventional electric system is shown in Table 6.

Table 6. Costs for installing conventional electric drop and pump system.

Conventional electric drop and pump items	Lifetime cost	Initial cost
	-------------- $	---------------
Electric drop	3,000	3,000
Electric (monthly charges)	3,440	0
Pump, mounted in well	750	750
Total	7,190	3,750

Assuming that maintenance costs are minimal and largely offsetting for the conventional electric and the solar system, the landowner's initial costs are $6,540 for the solar system (after expected tax credits and USDA renewable energy grants) versus $3,750 for the conventional electric system. The solar system becomes cost effective when long-term electricity costs are considered. The 1600 W solar system should provide adequate subirrigation water for a 15 to 20 acre corn field in an average year. Conventional electric systems appear more cost effective for fields larger than this where a single conventional electrical drop/pump can supply multiple fields, and where no dedicated utility poles are needed.

Wiring Solar Systems to Provide AC Electricity. Several area farmers have indicated their intent to construct solar trailers in 2008. Most have indicated that they desire to include solar components to enable the system to serve as a source of 110 volt AC power during the off-season. They intend to use the trailers for powering known loads at the farmstead (electric fences, etc) and do not intend to wire the systems into the electric grid. A preliminary design shows the necessary components for a solar pump trailer with off season AC power generation (Table 7). The AC components may be eligible for Federal rebates and USDA renewable energy grants (personal communication, Matthew Moore, USDA-RD).

Table 7. Component costs for a 1600 W system with off-season AC generation, without a grid connection.

Components	Cost
	-------- $ --------
Grundfos SQF IO101 Generator Interface Box	400
Battery Pack	800
Charge Controller	250
Modified Sine Wave Inverter, 120VAC Output	500
System assembly	500
Solar trailer	10,900
Total system cost	13,350

Lessons Learned Regarding System Safety and Flexibility. As previously detailed, the system utilized ten solar panels for the solar array. Each panel was rated at 120 W, with an output of 19.6 V and 6.12 A. The panels were wired in series so that final output was 196 V and 6.12 A. In retrospect, this was not a desirable wiring method. The currently available solar pumps can utilize DC electricity with an inflow varying from 30 to 300 V DC with a 1200 W maximum, but there is no significant benefit of providing greater than 90 V DC. From a safety standpoint, it would have been desirable to wire the system for 5 panels in series, and 1 parallel build at the end for an output of 98 V DC and 12.2 A. Exposure to 98 V DC and 12.2 A has been recommended over the system's existing output of 196 V and 6.12 A. From a future flexibility standpoint, it would have been beneficial to have used 12 panels instead of 10. A 12 panel system provides four parallel build options with 12, 6, 4, and 3 panels wired in series while a 10 panel system provides two parallel build options with 10 and 5 panels in parallel series. A 12 panel array provides the designer with additional flexibility for tailoring the voltage/amperage output for the largest variety of components. This flexibility can be valuable when designing a complex system such as a "summer DC irrigation/winter 110V AC power supply" as is being contemplated for future systems. Also, with expected solar panel lifetimes of 30 years or more, it is probable that components such as pumps, inverters, etc. will need to be replaced in the future. Future component selection will be much easier if designers have the ability to quickly adjust voltage/amperage output.

The solar pumping system in this project utilized electricity as generated. It did not have batteries that would allow for the system to store excess daytime electricity for nighttime use, thereby allowing 24 hour pumping. Battery storage could permit one pump system to subirrigate 30 to 40 acres rather than 15 to 20 acres as per the 1600 W system. However, total solar panel area would have to be doubled, and then further increased by a factor of 1.25 to account for typical energy losses when charging/discharging batteries. A 1600 W system would be expected to need approximately 4000 W of solar panels and a battery bank. The costs of this system are tabulated in Table 8.

Table 8. Component costs for a 4000 W system with wintertime AC production, but without grid hookup.

Components	Cost
	$
30 solar panels (approximately 130 W each)	15,600
Grundfos 60 SWF-3 Pump	1,600
Grundfos SQF IO101 Switch Box	400
Misc. splices, plates, nuts	500
Shipping for above	1,200
Two-axle trailer, 30 ft	2,000
Removable solar panel mount assembly	2,000
System Assembly	1,000
Battery Pack	1,200
Charge Controller	400
Modified Sine Wave Inverter, 120 VAC output	1,100
Total system cost	27,000

Carbon Dioxide Emissions Reduction. It was not the purpose of this study to quantify reductions in carbon emissions when replacing gasoline pumps with solar systems; however, the question has been asked frequently enough that a quick calculation is provided. The solar pump saved about 3 gal of gasoline/d while in operation (personal observation, Mark Wessell). Subirrigation was applied for a total of 68 d this year due to the drought. A more typical pumping period is about 60 d. The product of 60 d and 3 gal/d over a 25 year system lifespan resulted in a 4,500 gal reduction of gasoline consumed when using the solar pump system. Since each gallon of burned gasoline creates about 20 lbs of CO_2 (USDOE, 2008), the solar system could reduce gasoline CO_2 emissions by approximately 90,000 lbs over a 25 year lifespan.

Summary and Recommendations:

- The solar pump provided an average of 30,000 g/d when the panel was left flat, and provided approximately 42,250 g/d when the panel manually tracked the sun in 2007.
- Corn yield increased 35% with subirrigation in 2007.

- The solar pump subirrigated a field up to 15 acres in size. Newly available pumps may subirrigate fields up to 20 acres in size. Landowners should be prepared to provide additional water during extreme drought conditions.
- A solar pump system was more economical than a conventional electric system at this location.
- Solar panel configuration modifications can enhance safety and provide flexibility in matching future component power needs.
- A solar pump system may reduce CO_2 emissions by approximately 90,000 lbs over a 25 year lifespan.

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