Developing Wind and/or Solar Powered Crop Irrigation Systems for the Great Plains

B. D. Vick, L. K. Almas

Abstract. *Some small scale, off-grid irrigation systems (< 2.5 ha) that are powered by wind or solar energy are cost effective, but this article discusses ways to achieve an economical renewable energy powered center pivot irrigation system for crops in the Great Plains. It was found that partitioning the center pivot irrigation system between a winter crop and a summer crop improved the match of wind turbine power generation to irrigation energy required. It was also found that a solar-photovoltaic (PV) array was a better match to the irrigation energy requirement of a winter and summer crop than using only a wind turbine, but a wind/solar hybrid was a better match than wind alone. Although solar PV systems were shown to be a better match than wind turbines for irrigation power requirements, solar PV systems are more expensive than small wind turbine systems for large-scale irrigation water requirements in the Great Plains. Including on-farm uses for the excess wind and solar electricity instead of selling the electricity back to a utility company at usually low prices, improves the profitability of a renewable energy powered irrigation system significantly. For a utility electrical price of $0.10/kWh, a wind turbine installed price of $3000/kW, no loan required (e.g. no loan costs), and the excess renewable energy generated electricity used for on-farm use only, a payback period of seven to eight years was possible with no state or federal incentives. With 55% federal incentives and the same assumptions, a payback period of four to five years was possible. Also, if the assumed operations and maintenance costs doubled, the payback period increased about two years. However, cost reductions are still required for both wind and solar energy systems in order that renewable energy systems can be competitive without the need for state or federal incentives when loans at 90% of installed cost with a 6% interest rate are required.*

Keywords. *Solar, Wind, Irrigation, Great Plains, Texas High Plains, Crop, PV, Wind turbine, Cost, Payback, IRR.*

A considerable amount of the irrigated crops in the world are grown in the Great Plains of the United States (Univ. of Nebraska, 2010). In order to grow these crops or increase their yield in this region, water is pumped from underground aquifers for irrigation. The energy used for pumping the water is either fossil fuels or it is predominantly derived from them (e.g. electricity from electric utilities using coal and natural gas). Besides the widely held belief among climatologists that the burning of fossil fuels is the major cause of global warming, the anticipated increased costs of fossil-fuel/derived energy may force farmers to adopt renewable energy resources (i.e. wind, solar, or biodiesel). Many farmers in the Texas northern High Plains had to discontinue or reduce irrigating in 2001 because of a spike in natural gas prices (fig. 1). Due to the current low price of natural gas, natural gas-powered irrigation systems are currently less expensive than the utility grid-powered systems, but natural gas is a finite resource, and the price will inevitably increase when the supply decreases in the future.

Scientists at the USDA-Agricultural Research Service Conservation and Production Research Laboratory (CPRL) near Bushland, Texas, and the Alternative Energy Institute, West Texas A&M University (WTAMU), Canyon, Texas, began investigating the use of wind energy to pump water for irrigating crops in the Great Plains in the late 1970s. At the time, the use of wind energy as an energy source for irrigation was found to be cost prohibitive primarily because irrigation is needed only part of the year (Clark and Vosper, 1983). In 2000, it was found that irrigating a citrus orchard in the Rio Grande Valley of Texas was closer to profitability with a 10-kW wind turbine due to a good matching of irrigation water required and wind energy available, as well as the fact that the citrus orchard used irrigation water the entire year

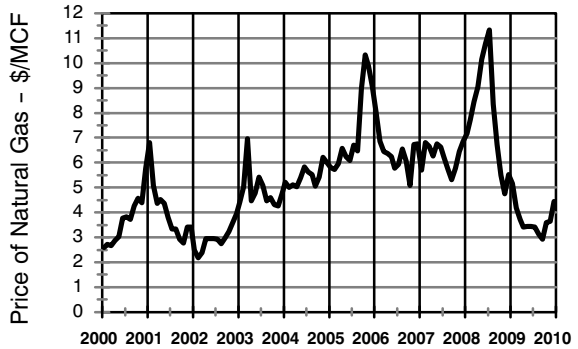

Figure 1. Price of natural gas in United States at the well head (International Energy Agency, IEA).

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The authors are **Brian David Vick,** Research Agricultural Engineer, USDA-Agricultural Research Service, Conservation and Production Research Laboratory, Bushland, Texas; and **Lal Khan Almas,** Associate Professor, West Texas A&M University, Canyon, Texas. **Corresponding author:** Brian Vick, USDA-Agricultural Research Service, Conservation and Production Research Laboratory, P.O. Drawer 10, Bushland, TX 79012-0010; phone: 806-356-5752; e-mail: Brian.Vick@ars.usda.gov.

(Vick et al., 2000). In 2001, the use of wind energy for large-scale crop irrigation was revisited by the staff at CPRL at the urging of area farmers who were concerned that increased natural gas prices were reducing their profit margin. Again, the economics of using wind energy for irrigation were marginal at best (Vick et al., 2001). In 2006-2007, wind-assisted irrigation for the Texas northern High Plains and southwestern Kansas was studied by Texas AgriLife Extension Service (Gaskins et al., 2007). The economics were found to be uncompetitive compared to switching completely to utility supplied electricity (i.e. no wind turbine component) due to the mismatch of the irrigation energy requirement and available wind resources. An additional economic finding was the resistance of electrical utilities to purchase wind generated electricity at more than a few cents per kWh during periods when either irrigation was not performed or the amount of wind generated electricity exceeded irrigation power requirements. Growing both a summer crop and a winter crop with a wind turbine was shown to be a better match to irrigation water requirement, and solar energy was found to be a better match to irrigation requirement of a summer and winter crop than wind energy for the Great Plains (Vick, 2010). The CPRL Renewable Energy Team recently began a five-year project plan in which one goal is to develop a renewable energy system for large-scale crop irrigation that will also be cost competitive with current fuel choices.

The qualitative amount of irrigated acreage in the United States can be seen in figure 2. With regards to the Great Plains, the greatest irrigated area is in Nebraska, Kansas, the northern and southern High Plains of Texas, and eastern Colorado. The quantitative amount of irrigation can be seen in figure 3 during the period from 2000 to 2009 for the high irrigation states in the Great Plains. Nebraska has the highest amount of irrigated area followed by Kansas, Texas northern High Plains, Texas southern High Plains, and eastern Colorado.

In 2004, Entegrity (a 50-kW wind turbine manufacturer located in Charlottetown, Canada) asked the CPRL Renewable Energy Team to investigate the use of their wind turbine for pumping water for irrigation in the Texas High Plains. During this investigation, it was determined that combining a winter crop with a summer crop resulted in a much better match of irrigation energy required and wind energy available. The irrigation energy demand for winter wheat is a good match to wind turbine energy since the maximum wind turbine energy normally occurs in the spring when the highest irrigation requirement occurs and the minimum wind turbine energy normally occurs in summer which coincides with no irrigation requirement (fig. 4). Wind energy is not a good match to a summer crop because the largest irrigation water demand is in the summer when the winds are usually lowest (fig. 5). However, when half of the center pivot quarter section was planted in winter wheat and the other half was planted in cotton, the 50-kW wind turbine electrical generation was a much better match to the irrigation energy required (fig. 6). The deficiency in wind energy in the summer in figure 6 implied that adding solar energy would improve the match to the irrigation energy required. This hypothesis was confirmed when the wind and

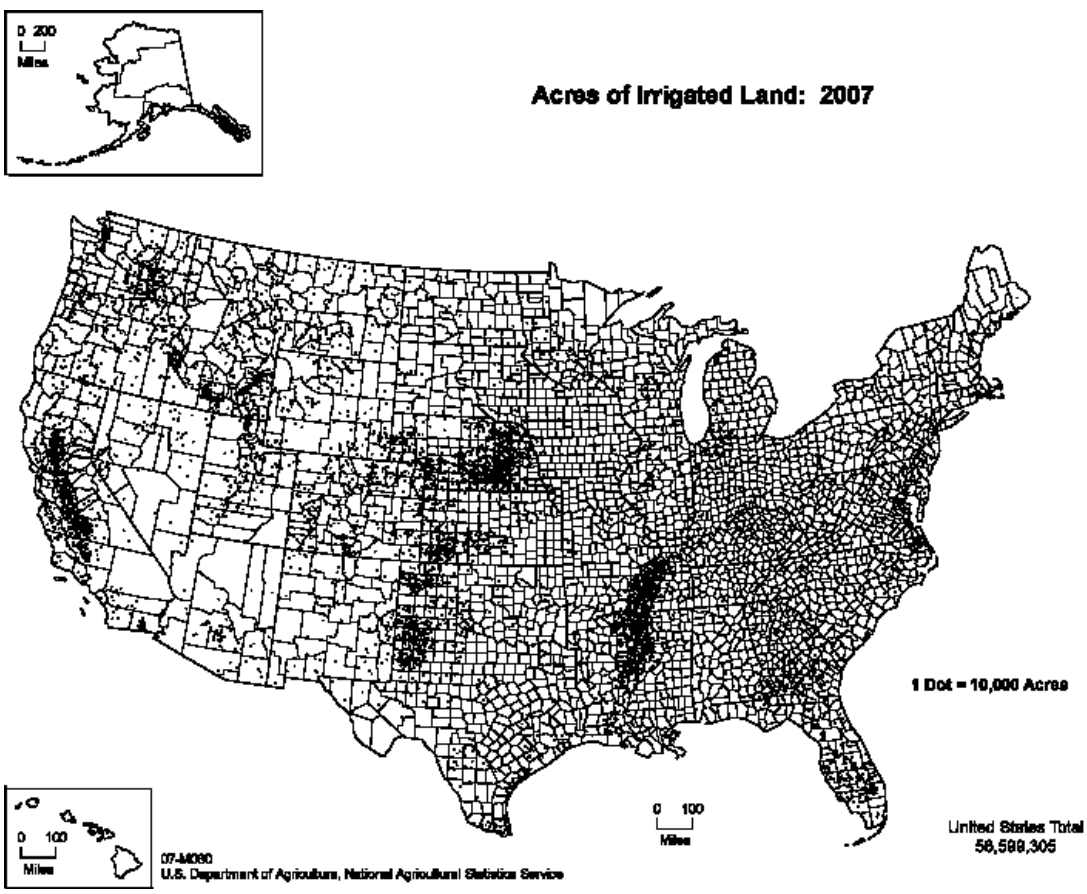


Figure 2. Irrigated land in the United States (USDA-NASS, 2007a).

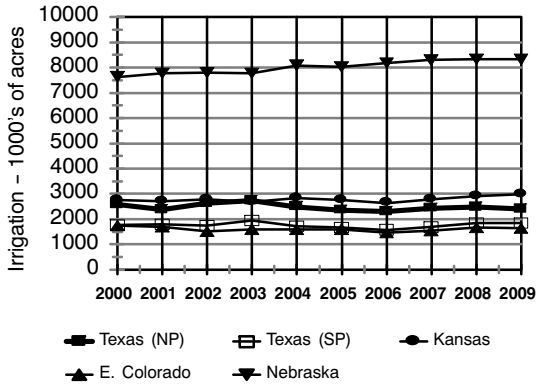
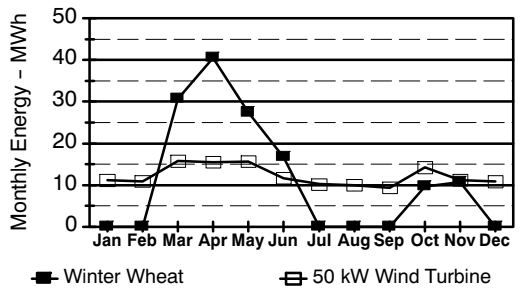
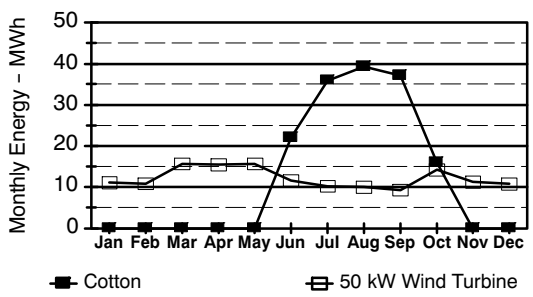


Figure 3. Total irrigated acres of crops (USDA-NASS, 2010).



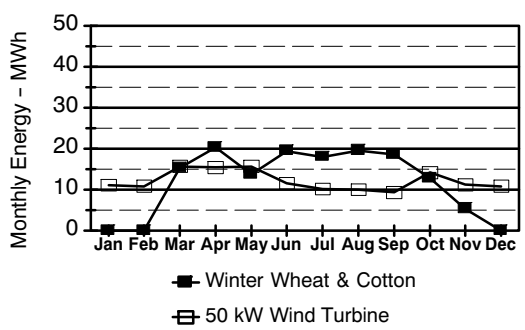
Note: Texas Panhandle, Center Pivot, assume 1 ha–mm requires 6 kWh of energy.

Figure 4. Irrigating winter wheat (51 ha) with a 50-kW wind turbine (25-m hub ht.).



Note: Texas Panhandle, Center Pivot, assume 1 ha–mm requires 6 kWh of energy.

Figure 5. Irrigating cotton (51 ha) with a 50-kW wind turbine (25-m hub ht.).



Note: Texas Panhandle, Center Pivot, assume 1 ha–mm requires 6 kWh of energy.

Figure 6. Irrigating winter wheat (25.5 ha) and cotton (25.5 ha) with a 50-kW wind turbine (25-m hub ht.).

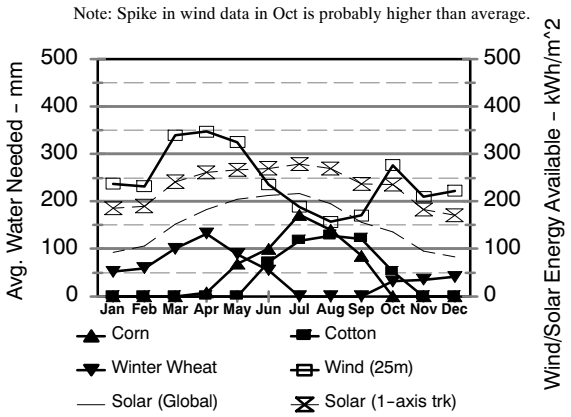


Figure 7. Average irrigation water required and wind/solar energy available (Texas Panhandle).

solar energy available were compared with the irrigation requirement of crops in the Texas High Plains (fig. 7). The solar energy available is shown for two different pyranometer measurements: global and 1-axis tracking. Global radiation is the total incoming radiation (direct and diffuse from solar disk and sky dome) on a horizontal plane on the earth's surface while 1-axis tracking is incoming radiation (direct and diffuse from solar disk, sky dome, and ground) at a fixed latitude tilt angle (35°) which tracks the sun during the day. These solar resource data were collected and estimated for Amarillo, Texas (~16 km east of CPRL) over the period 1961-1990 with a data uncertainty of ±9% (Marion and Wilcox, 1994). The global solar energy is higher than wind energy for July and August, but the solar energy for 1-axis tracking with latitude tilt is higher than the wind energy for June through September. The irrigation required for the various crops was based on the average water requirement of each crop and the average rainfall at CPRL (Texas northern High Plains, primarily north of the Canadian River) and Lubbock, Texas (Texas southern High Plains). It should also be noted there is an irrigation requirement shown for winter wheat in December, January, and February in figure 7 though no irrigation requirement is shown in figures 4 and 6. This is because additional moisture is usually needed for winter wheat during winter, but moisture is not usually applied by irrigation due to freezing conditions. However, low elevation spray applications (LESA) can avoid icing problems if spray is applied below the truss rods.

Therefore, two important criteria for improving the match of renewable energy to irrigation water requirement in the Great Plains are:

- growing both a winter and a summer crop,
- adding solar power to a wind powered system.

The winter crop in the Great Plains with the highest number of irrigated acres is winter wheat. The amount of winter wheat that was irrigated in the high irrigation states in the Great Plains can be seen in figure 8. Kansas and the Texas northern High Plains have the largest amount of irrigated winter wheat in the Great Plains. Kansas probably would be a good candidate for using renewable energy to pump water for irrigation especially since a net metering rule (up to 200 kW) was passed in Kansas state legislature in May 2009 which greatly improves the likelihood of wind and solar powered irrigation in Kansas (NCSU, 2010). However, our knowledge of: the wind/solar resource, the evapotranspir-

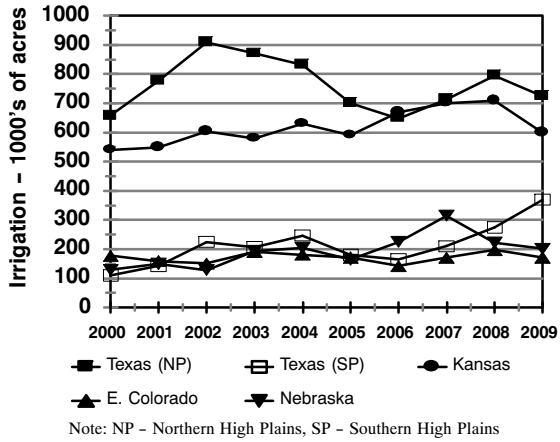


Figure 8. Irrigated acres of winter wheat in Great Plains (USDA-NASS, 2010).

ation (ET) required for crops, and the rainfall average for the Texas northern High Plains resulted in the analysis for this article focusing on just the Texas northern High Plains. The four main crops that are irrigated in the Texas northern High Plains can be viewed in figure 9. The two crops with the largest irrigated acreages are corn and winter wheat. Cotton was similar to corn in irrigated land until 2007 when the push for corn to produce ethanol and the failure of cotton to meet expected yields caused a large shift in planted acreage.

Objective

Our main objective was to evaluate the use of renewable energy (e.g. wind, solar, wind/solar hybrid) for supplying the power (or a portion of the power) for a center pivot crop irrigation system for a winter crop and a summer crop in the Texas northern High Plains. A secondary objective was to determine obstacles and/or changes that need to be overcome and/or implemented, respectively, in order to achieve a cost-effective renewable energy powered irrigation system.

Materials and Methods

To meet our objectives, it was necessary to determine the monthly energy demand of different crops grown in the Texas northern High Plains, and what size wind turbine or photovoltaic (PV) array was necessary to meet the demand

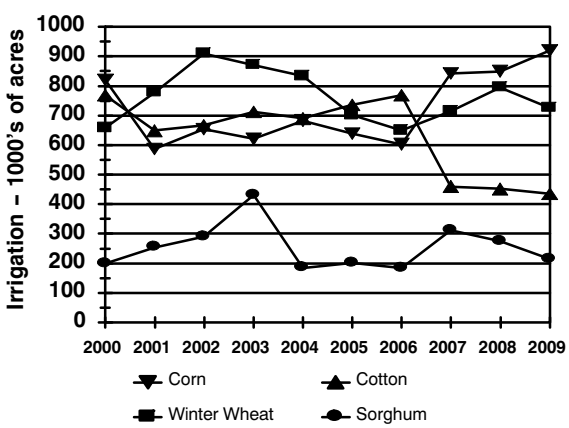


Figure 9. Irrigated crops in the Texas northern High Plains (USDA-NASS, 2010).

based on the wind and solar resource, respectively. In addition, it was also necessary to determine the costs and income of the different wind, solar, and wind/solar hybrids, and determine other ways that use of renewable energy equipment can save money or produce income.

In order to determine the monthly irrigation energy demand, it was necessary to know the average monthly evapotranspiration (ET) of the different crops, average monthly rainfall, and average monthly energy to meet the irrigation demand. The average monthly ET for different crops and the average monthly rainfall have been measured and recorded for Bushland, Texas, by CPRL personnel. The monthly irrigation energy demand was determined by Texas AgriLife Extension Service at Amarillo, Texas. Also, it was assumed that a typical amount of energy required to pump 10.3×10^{-3} ha-m (1 acre-in.) of irrigation water in the Texas northern High Plains was 62 kWh (New, 2004). According to (Guerrero et al., 2010), the value 62 kWh is representative of a 103-m (338-ft) pumping lift (pumping lift represents static water level plus additional drawdown depth). Also included in the 62-kWh value is the energy required to achieve an operating pressure of 179 kP (26 psig) and a flow rate of 2270 L/min (600 gal/min). For the estimation of energy required for different pumping lifts, the following equation should be used:

Energy required in kWh to pump 10.3×10^{-3} ha-m =

$$0.3687 \text{ (pumping lift in m)} + 24.04 \qquad (1)$$

To determine the monthly energy generated by different wind turbines, it was necessary to know: (1) average hourly wind speed histogram for different heights, (2) average monthly air density, (3) power curve (e.g. wind turbine power versus hub height wind speed) of wind turbine(s), and (4) estimated availability (availability is defined as percentage of time during year the wind turbine is operable or 100% minus % of downtime) of the wind turbine. The hourly wind speed histograms used were obtained from the Alternative Energy Institute (AEI) at WTAMU, Canyon, Texas (www.windenergy.org). The wind speed data used in the analysis were gathered ~14 km NNE of Amarillo, Texas, at 25- and 40-m (82- and 131-ft) heights over a three-year period (1995-1997). The average monthly air density data were determined from hourly measurements of air temperature and barometric pressure at CPRL (elevation = 1,159 m, about 30 km southwest from wind speed measurement location) from 1983 to 1999. The power curve used was measured at CPRL for a 50-kW (15-m rotor diameter) Atlantic Orient Corp. (AOC, Norwich, Vt.) wind turbine and was corrected to sea level standard day conditions. The 50-kW AOC wind turbine power curve was measured by CPRL personnel. The CPRL has tested a 40-kW wind turbine since 1982, and the average availability of this wind turbine was determined to be 90% during the period from 1983 to 2002 (Clark, 2004). The equation for the power of a wind turbine is shown below, and helps in understanding how the parameters wind speed, rotor diameter, air density, and aerodynamic design of rotor (e.g. Cp) influence the wind turbine power generation.

$$\text{Power}_{wt} = 1/2\ Cp\ \rho\ V^3\ A_{swept} \qquad (2)$$

where

$Power_{wt}$ = power of wind turbine (W)
Cp = power coef. of wind turbine, theoretical maximum is 0.593 but for well designed rotors peak Cp ~ 0.40
ρ = air density (kg/m^3)
V = wind speed (m/s)
A_{swept} = swept area of wind turbine blade rotor (m^2)

To determine the monthly energy generated by different PV arrays, it is necessary to know: (1) the average daily solar energy for each month, (2) the efficiency of the PV modules at 25°C, (3) the PV module efficiency change with temperature, (4) the average monthly temperature of modules, (5) inverter efficiency from DC to 3-phase AC, and (6) the various efficiencies of a field installation. As mentioned previously, the solar energy data for each month were collected/estimated for Amarillo, Texas (~16 km east of CPRL) over the period 1961-1990 (Marion and Wilcox, 1994). The PV module efficiency of thin film and multi-crystalline silicon modules has been measured at CPRL in various solar water pumping experiments. Efficiency is defined as ratio of energy output to energy input (usually expressed as a percentage). So the PV module efficiency is the ratio of DC power output from the PV module to solar energy incident on the surface of the PV module. The measured efficiency of thin-film modules (like cadmium-telluride and amorphous-silicon) has been in the 3% to 4% range (First Solar cadmium-telluride modules are reported to have an efficiency in the 9% range and sell for under $1/Watt but only sold for utility scale multi-megawatt projects) while that of multi-crystalline modules is in the 12% to 14% range (selling in the $2 to $3/Watt range for projects under 200 kW). For the analysis in this article we assumed 14% efficiency at standard test conditions (e.g. irradiance of 1000 W/m^2, 25°C module temperature, air mass of 1.5). As the module temperature increases, the efficiency of crystalline modules decreases about 0.5% per degree Celsius above 25°C (e.g. for a module temperature of 45°C, the PV efficiency would decrease to 12.6%). The average monthly PV module temperature (fixed position modules) was measured at CPRL from 1996 to 2000 and then again in 2003 (Vick and Clark, 2004), and the average monthly module temperature was used in decreasing PV efficiency from 14%. The inverter efficiency was assumed to be 95% (CEC, 2010). The remainder of the derating factor of the PV system was composed of: nameplate rating (95%), soiling (95%), panel mismatch (98%), wiring losses (97%), diodes and connectors (99.5%), and system availability (98%) which came to a total efficiency of 83.6%. These efficiencies came from an online computer program (NREL, 2010). There is a 10% to 12% uncertainty in the PVWATTS computer program (Hoff and Perez, 2010) which reinforces the need for experimental verification.

For the economic analysis of the different wind, solar, and hybrid wind/solar systems analyzed, we used a cash flow Excel spreadsheet available on the web (Bergey, 2010). The profitability of different capacities of wind turbines (50, 100, and 150 kW), and a hybrid 50-kW wind turbine and a 90-kW single-axis solar PV system for irrigating winter wheat and corn on a quarter section of land (51 ha) was estimated. It was assumed that the wind turbine(s) were installed at a 25-m (82-ft) hub height near Amarillo, Texas, and they generated the same monthly energy as an AOC 50-kW wind turbine. For larger wind turbine power ratings of 100 and 150 kW, the monthly electricity generated by AOC 50 kW was doubled and tripled, respectively. The installed cost of wind turbines in the 40- to 100-kW size ranged in price from $2,750 to $5,900/kW (table 1).

Life cycle cost (LCC) is defined (http://www.business-dictionary.com/definition/life-cycle-cost.html) as the sum of all recurring and one-time (non-recurring) costs over the full life span or a specified period of a good, service, structure, or system. It includes purchase price, installation cost, operating costs, maintenance and upgrade costs, and remaining (residual or salvage) value at the end of ownership or its useful life. For the LCC of a wind turbine we assumed:

- 25-m (82-ft) hub height,
- average hourly wind distribution from 1995-1997 at 25-m (82-ft) hub height near Amarillo, Texas,
- availability of 90%,
- annual operation and maintenance cost (see eq. 3),
- 20-year life of the wind turbine,
- all the energy generated would be used,
- salvage cost would equal removal cost.

The annualized cost makes the same assumptions as for LCC, but also includes the value of money (assumed 6%/year) by investing in the wind turbine. If the hub height of the wind turbine was increased to 40 m (131 ft), the estimated increase in energy output is ~12% based on our analysis of measured wind speed data near Amarillo, Texas, from 1995 to 1997. Most small wind turbine manufacturers claim higher availability than 90%, but they are not likely to warranty the higher availability (e.g. higher production) for the life of the wind turbine. Solar PV array installations in the 90 to 200 kW size varied in price from $5,000 to $6,000 per kW. A single-axis 26.4-kW PV array was installed in the San Luis Valley in Colorado on 31 March 2010 at a cost of $5,300 per kW.

Because corn and winter wheat are currently the greatest irrigated acreages in the Texas northern High Plains, this analysis concentrates on how well solar and wind energy

Table 1. Physical sizes, ratings, and cost estimations of small wind turbines for crop irrigation.

Turbine Model	Power Rating (kW)	Rotor Diameter (m)	Installed Cost ($)	Annual Energy (MWh)	$/Power Rating ($/kW)	LCC 20 yr ($/MWh)	Annualized Cost ($/MWh)
Enertech E44	40 kW @ 13.4 m/s	13.4	110,000	72[a]	2,750	86.39	143.20
AOC 15/50	50 kW @ 11.2 m/s	15.0	240,000	146	4,800	92.19	153.32
Endurance E3120	55 kW @ 11.2 m/s	19.2	325,000	189	5,900	95.98	159.92
Northwind 100	100 kW @ 15.2 m/s	21.0	550,000	250	5,500	120.00	201.80

[a] Actual production of 1982 E44 (82-ft hub height) at CPRL (Bushland, Tex. 1995-1997, 90% availability).

generation match the irrigation energy requirement of these two crops when grown in equal amounts on a center pivot quarter section (51 ha). The irrigation water required was based on the average monthly ET of corn and winter wheat at CPRL minus the average monthly rainfall at Bushland over the period 1983 to 2009.

Since the economics of wind energy for irrigation are much improved if the excess wind energy is used for on-farm uses, an analysis of the matching between wind energy generated and green house energy demand was also conducted. Assumptions for the greenhouse were:

- Only 1/3rd of solar radiation is transferred to the ground
- The greenhouse is semi-cylindrical made of two layers of plastic with an air gap between the layers.
- The heat coefficient = 3.97 W/(m^2 °C)
- Maintain a temperature of at least 15°C (59°F) inside the greenhouse.

We estimated payback in years and the internal rate of return (IRR) in percentage (over 20-year period – the life of wind turbines is usually estimated at 20 years) for various financial scenarios with wind turbine and combination of wind turbine and PV array. The payback period represents the time it takes to reach positive cash flow, and the IRR represents the quality of wind turbine or hybrid wind/PV system as investment. Operation and maintenance costs for both the wind turbine(s) and single-axis tracking PV array were assumed by the following equation:

$$\text{O\&M Cost per year} = \$10/\text{MWh} \times (\text{annual MWh production}) \quad (3)$$

The following parameters were used in the calculations of payback period and IRR:

- Selling excess wind-generated electricity at a typical buyback rate for an Investor Owned Utility ($0.025/kWh) or using the surplus electricity for other on-farm electrical needs ($0.10/kWh which is average 2009 Texas High Plains rural price).
- Assuming no loan required or with a loan (for loan assumed 10% down payment, 6% interest rate, 8-year loan period)
- Three cases analyzed, Case 1 – no federal incentives, Case 2 – 30% federal tax credit, and Case 3 – 30% federal tax credit and 25% USDA Renewable Energy for America Program (REAP) grant (www.dsireusa.org).
- No inflation rate was assumed on utility supplied electricity or for operation and maintenance of wind and wind/solar systems.
- The system was depreciated over six years assuming the farmer was in 35% tax bracket.
- O&M costs began in first year and were same as in equation 3.

Results and Discussion

Using Solar and Wind Energy for Irrigation in the Texas Northern High Plains

How well the irrigation energy demand of corn and winter wheat on a center pivot irrigation system quarter section (51 ha) can be met by three different solar PV arrays is presented in figure 10. For the first case the modules were assumed to be fixed at 20° (Latitude = 35.2°N). Peak energy requirement for corn occurs in July when the optimum PV array tilt angle at Amarillo, Texas, is about 18°. Since PV arrays are made up of individual modules, each with a few hundred Watt power output, precise power requirements can be achieved. The estimated power rating of the PV array for fixed modules at 20° is 196 kW. If motorized trackers are installed to track the sun from sunrise to sunset (e.g. single-axis tracking system), the size of the PV array can be reduced to 146 kW. If a two-axis motorized tracking system is used, the rated power is still 146 kW, but additional solar power is available during the winter for other farm energy requirements. It is evident from figure 10 that solar energy is a good match to irrigating winter wheat and corn in the Texas northern High Plains.

Using wind turbine(s) to meet the irrigation energy requirement for a center-pivot irrigation system on a quarter section of winter wheat and corn is shown in figure 11. In order to meet the peak irrigation water requirement in July, a wind turbine rating of ~130 kW is required (e.g. if a 50-kW AOC is used, then a farmer would need three turbines for a total rating of 150 kW). Even if four wind turbines were required, they could be located at the corners of a center pivot quarter section and should not significantly interfere with each other since the separation between wind turbines would be well over the 10 rotor diameters. Depending on the wind turbine blade rotor size – a lower kW wind turbine power rating may be all that is required. The Endurance Wind Power 55-kW wind turbine has a 19.2-m (63-ft) blade rotor diameter and this wind turbine (assuming a 90% availability and published power curve) would generate 30% more annual energy than the AOC wind turbine, but 40% more energy during July. Therefore, two Endurance Wind Power 55-kW wind turbines (i.e. total rated power 110 kW) should be able to meet the peak electrical load of corn and winter wheat during an average July. Increasing the hub height of the wind turbine from 25 to 40 m did not significantly increase the energy of the wind turbine in July; however, a higher height should result in less maintenance because more turbulent air usually occurs closer to the ground, and more turbulent air increases operation and maintenance costs (Gipe, 2004).

The hub heights of the large MW size wind turbines vary from 60 to 100 m, and wind turbines at these heights take advantage of the low level jet in the Great Plains. The annual

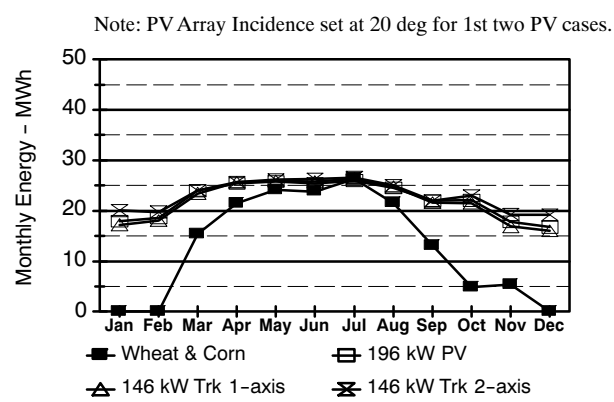
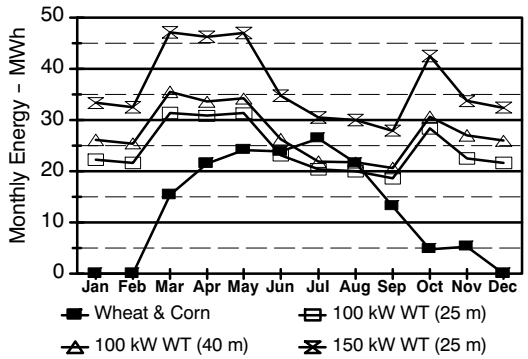


Figure 10. Irrigating winter wheat (25.5 ha) and corn (25.5 ha) with solar-PV array.



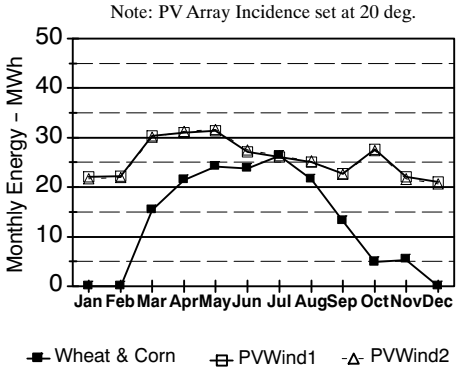
Note: Texas Panhandle, Center Pivot, 1 ha-mm requires 6 kWh of energy.

Figure 11. Irrigating winter wheat (25.5 ha) and corn (25.5 ha) with wind turbine(s).

wind energy available should be at least 50% more than at a 25-m hub height, but the cost of the tall tower would be too expensive for this size wind turbine. Comparing figures 10 and 11, the solar PV array is a better match to the irrigation energy requirement than with wind turbine(s).

Two cases of combining a solar-PV array with a 50 kW wind turbine are depicted in figure 12 which again was to meet the irrigation energy requirement for a center pivot quarter section (51 ha) of winter wheat and corn. The first case was for a fixed PV array at 20° incidence angle, and the size of the PV array is estimated to be 120 kW when combined with the 50 kW wind turbine. For the second case, a single-axis tracking system was assumed and the PV array size could be reduced to 90 kW. Both cases assume the wind turbine is at a hub height of 25 m. Both cases predict essentially the same monthly energy production. An advantage of hybrid wind/solar systems is that reliability is improved because the irrigation system is not as dependent on whether the sun is shining or the wind is blowing on a particular day. Currently the cost of the tracking system is approximately the same as the cost of the additional PV modules needed for a fixed system, however, the tracking systems may decrease in price in the future.

Note: PV Array Incidence set at 20 deg.



Note: PVWind1 = 120 kW PV with 50 kW WT (25 m)
PVWind2 = 90 kW PV 1-axis Trk with 50 kW WT (25 m)

Figure 12. Irrigating winter wheat (25.5 ha) and corn (25.5 ha) with PV array and wind turbine.

For all the wind, solar, and hybrid wind/solar systems shown in this analysis, the average monthly moisture, average wind speed, average crop water requirements, and average solar irradiance values were assumed. Obviously there will be months when the average does not occur. Fortunately during drought conditions, the solar and wind energy usually increase which should compensate for decreased rainfall. Because crops are normally sensitive to water stress during certain growth stages, there should be a backup energy system available to power the irrigation system when solar and wind generated electricity are not available.

In Texas, according to the USDA 2008 Farm and Ranch Irrigation Survey (USDA-NASS, 2007b), the main energy types used to power irrigation systems are utility supplied electricity, natural gas, and diesel – 61%, 30%, and 8%, respectively. These irrigation energy percentages are different than those reported in the USDA 1998 Farm and Ranch Irrigation Survey when the percentages of utility supplied electricity, natural gas, and diesel were 34%, 30%, and 35%, respectively. So, from 1998 to 2008, the percentage of Texas farmers using natural gas to power their irrigation systems remained the same, but the change in percent of farmers who quit using diesel for powering their irrigation systems was equivalent to the change in percent of those farmers who started using utility supplied electricity for powering their irrigation systems. Depending on the type of wind turbine chosen (e.g., induction generators need excitation from utility line or a diesel generator while permanent magnet alternators or direct drive systems do not require utility line excitation), if 3-phase 480-V utility electricity is not available, this would prevent the use of a wind turbine (unless diesel generator with accompanying controller for interconnecting wind turbine was available or purchased).

The renewable energy irrigation systems connected to the utility electrical grid could use the utility electricity as a backup when wind and/or solar energy are insufficient to supply the irrigation demand load. Battery storage is not recommended because typically the cost of the renewable energy system will double with the addition of batteries. Mechanical windmills have worked successfully in the Great Plains for over 100 years by storing water in an additional tank on windy days and watering cattle from a storage tank on calm days. Similarly for solar energy systems, water is stored on sunny days and used on cloudy days. Storing more than a few days of water for irrigating a quarter section would require too large a reservoir, but it would help to provide a continuous water supply to the crop during calm and/or cloudy days. A diesel engine used for driving the pump for irrigation could use biodiesel with some modifications and the fuel (e.g. soybeans or cottonseed) could be grown and manufactured on the farm using the excess renewable energy during the fall, winter, and spring. At CPRL we have operated diesel generator units on 100% biodiesel without any damage to the engines (Clark and Eggleston, 1999). Unfortunately the natural gas engines are similar to gasoline engines using a spark plug, so they could only operate on ethanol which probably could not be manufactured on the farm. Therefore for natural gas irrigation systems, the natural gas engine would need to be converted to a 3-phase AC 480-V electrical generator to power submersible electrical irrigation pumps. Due to declining water flow rate from wells in the Texas

Panhandle, most turbine-type pumps are being replaced by submersible pumps (Colaizzi, 2010).

Uses of Excess Wind/Solar Energy Generated

As will become apparent in the "Economic Analysis" section below, using excess renewable energy generated electricity for other income sources on the farm will significantly improve the profitability on the farm. Since irrigation is not performed during the winter months (December, January, and February) in the Texas northern High Plains, all of the electricity generated by the wind system is available. The diurnal comparison of greenhouse energy required for heating versus energy generated by a 50-kW AOC wind turbine at 25 m height can be seen in figure 13. The size greenhouse that could be powered by excess wind energy was only 6.1 × 12.2 m or 74.4 m^2.

If a solar-PV/wind hybrid system was used, additional solar-PV energy would be available. Passive solar devices like a thick wall or barrels of water could be used to store solar energy during the day and the heat would be released at night when it is most needed. For the period from 15 January 2009 to 17 February 2009, the energy required per unit surface area of greenhouse was estimated to be 35.5 kWh/m^2, but during the same period, a local greenhouse using natural gas for heating used the equivalent of 91.1 kWh/m^2 which would imply the area of the greenhouse size might be even less than 74.4 m^2.

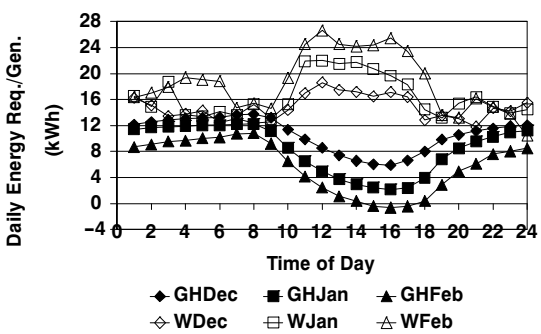


Figure 13. Greenhouse energy required vs. 50-kW wind turbine energy generated (winter, CPRL, 2008-2009).

Although greenhouses in this preliminary calculation do not appear to be a good use of excess renewable energy, there are many other possible on-farm uses for the energy. One possible use of the excess renewable energy is in the production of biodiesel from crops grown on the farm which would be used to power farm machinery. The excess renewable energy electricity could also be used in the production of hydrogen through electrolysis which could be used in fuel cells if fuel cells become economical to power farm machinery.

If the wind turbine and or solar-PV system were connected to a utility, the excess electricity could be sold to the utility. However, the investor-owned utility (IOU) and cooperatives in the Texas northern High Plains have resisted buying back the excess wind/solar electricity at a retail price. The IOU (Xcel Energy) will usually only pay avoided cost or fuel adjustment cost which is only a few cents per kWh for excess electricity generated, but also sometimes require demand charges which usually cancel out any money made from sale of excess renewable energy. Electrical Cooperatives in the Texas northern High Plains area (most irrigation systems in Texas are in Electrical Cooperative areas) presently don't pay for excess generated renewable energy electricity.

Economic Analysis

Using $3,000/kW installed price for the wind turbine(s) and $5,300/kW for single-axis tracking PV array, tables 2 and 3 were produced. In tables 2 and 3, we estimated payback in years and the internal rate of return (IRR) in percentage (over a 20-year period – the life of wind turbines is usually estimated at 20 years). Table 2 depicts wind turbines of different power ratings (50, 100, and 150 kW) and one hybrid (50-kW wind turbine and 90-kW 1-axis tracking PV array) which would be used to supplement/replace utility supplied electricity for crop irrigation systems in the Texas Panhandle for different financial scenarios discussed in Materials and Methods.

If operation and maintenance cost doubled, then paybacks increased about two years. There was a significant improvement if the surplus renewable energy could be used by the customer for some other use rather than selling back

Table 2. Supplementing/Replacing utility electricity at $0.10/kWh with 50-, 100-, and 150-kW wind turbine(s) and hybrid wt/pv for irrigating half corn and half winter wheat on a center pivot quarter section of land.

Elec. Surplus Sell/Use ($/kWh)	90% Loan (Y/N)	Fed. Tax Credit (%)	USDA REAP Grant (%)	wt/pv 50/0 Payback (years)	wt/pv 100/0 Payback (years)	wt/pv 150/0 Payback (years)	wt/pv 50/90 Payback (years)	wt/pv 50/0 IRR (%)	wt/pv 100/0 IRR (%)	wt/pv 150/0 IRR (%)	wt/pv 50/90 IRR (%)
0.025	No	None	None	10.2	12.3	16.0	> 20	6.5	4.3	2.0	–
0.100	No	None	None	7.5	7.4	7.1	14.7	10.4	10.5	10.5	2.8
0.025	Yes	None	None	17.5	> 20	> 20	> 20	2.1	–	–	–
0.100	Yes	None	None	12.2	12.7	12.7	> 20	8.8	9.1	9.1	–
0.025	No	30	None	7.2	8.8	11.3	> 20	11.0	8.3	5.5	–
0.100	No	30	None	5.3	5.3	5.3	10.3	15.8	15.9	15.9	6.5
0.025	Yes	30	None	17.3	> 20	> 20	> 20	2.5	–	–	–
0.100	Yes	30	None	12.4	12.5	12.5	> 20	9.6	9.8	9.8	–
0.025	No	30	25	5.5	6.7	8.4	13.1	15.3	12.1	8.9	3.9
0.100	No	30	25	4.2	4.1	4.1	7.7	21.2	21.3	21.3	10.0
0.025	Yes	30	25	17.1	> 20	> 20	> 20	2.7	–	–	–
0.100	Yes	30	25	12.5	12.4	12.4	> 20	10.1	10.3	10.3	–

to utility at a lower price of $0.025/kWh. Therefore, when installing the renewable energy system for irrigation, other sources of income on the farm that require electricity are an important consideration in determining feasibility. The payback period was reduced and the IRR was improved significantly if no loan was required. Obviously adding the federal incentives (Federal Tax Credit and USDA REAP Grant) improved the profitability, but unless the incentives are extended (the 30% Federal Tax Credit ends on 31 December 2016 and the 25% USDA REAP grant ends on 31 December 2012), there will not be any remaining federal incentives available. There currently are no state incentives for the Texas High Plains. Whether or not there is an incentive, if selling the excess electricity back to the utility at $0.025/kWh, it is more profitable to use a 50-kW wind turbine (e.g. the higher the wind turbine rating, the higher the payback period and the lower the IRR). If a farmer can use the excess renewable electricity (worth $0.10/kWh to farmer), the payback periods and IRR's are the same for 50-, 100-, or 150-kW wind turbines. The hybrid wind/solar irrigation system was the least profitable system due to the greater costs for solar systems.

The average fuel price for natural gas powered irrigation systems in the Texas Panhandle for 2010 was estimated to be $0.159/m^3 [e.g. $0.018 above the Well Head price of $0.141/m^3. To convert $/m^3 to $/mcf ("mcf" represents 1000 cubic feet), multiply above numbers by 28.3.]. Table 3 represents a 50-kW wind turbine replacing (with electrical utility assistance) a natural gas powered irrigation system for two different prices ($0.159 and $0.353/m^3). The equivalent $/kWh price for natural gas irrigation systems was calculated by the following equation:

$$\text{Natural gas price (\$/kWh)} = \$/m^3 \times m^3/(\#\ \text{kWh}) \times \text{elec. engine \& pump eff.} / \text{natural gas engine \& pump eff.} = \$/m^3 \times m^3/(301.6\ \text{kWh}) \times 67.5\%/18.5\% \quad (4)$$

The average overall efficiencies used for electrical and natural gas irrigation power plants came from Fipps and Neal (1995).

If the field price of natural gas was $0.159/m^3, the only case with an acceptable payback period (7.9 yr) and IRR (9.7%) was if:

- excess wind generated electricity was used on the farm and not sold back to utility;
- no loan was required; and
- both the Federal Tax Credit and the USDA REAP grant were used.

If the well head natural gas price increases to $0.282/m^3, that would be equivalent to the current utility electrical price of $0.10/kWh, and the analysis shown in table 2 would be applicable (unless a standby electrical generator was required if no 480V 3-phase AC electricity was available). If the well head natural gas price increases to $0.335/m^3 (which it has in past – see fig. 1), that would be equivalent to estimated utility electrical price of $0.121/kWh.

If 480-V 3-phase AC utility electricity was available, the wind turbine could either be an induction generator or a permanent magnet alternator (PMA). If 480-V 3-phase AC utility electricity was not available, either a diesel genset [at least at the same power rating of wind turbine(s) required], or a direct drive PMA could be used.

Table 3. Replacing natural gas at $0.159 and $0.353/mcf with 50-kW wind turbine/utility electricity for irrigating half corn and half winter wheat on a center-pivot quarter section of land.

Nat. Gas Field Price ($/m^3)	Elec. Surplus Sell/Use ($/kWh)	90% Loan (Y/N)	Fed. Tax Credit (%)	USDA REAP Grant (%)	Payback (years)	IRR (%)
0.159	0.025	No	None	None	19.3	0.3
0.159	0.054	No	None	None	15.2	2.5
0.159	0.025	Yes	None	None	> 20	–
0.159	0.054	Yes	None	None	> 20	–
0.159	0.025	No	30	None	13.5	3.6
0.159	0.054	No	30	None	10.5	6.2
0.159	0.025	Yes	30	None	> 20	–
0.159	0.054	Yes	30	None	> 20	–
0.159	0.025	No	30	25	10.1	6.7
0.159	0.054	No	30	25	7.9	9.7
0.159	0.025	Yes	30	25	> 20	–
0.159	0.054	Yes	30	25	> 20	–
0.159	0.025	No	None	None	8.5	8.9
0.353	0.121	No	None	None	6.1	13.4
0.353	0.025	Yes	None	None	14.5	6.0
0.353	0.121	Yes	None	None	10.4	15.4
0.353	0.025	No	30	None	5.9	13.9
0.353	0.121	No	30	None	4.4	19.6
0.353	0.025	Yes	30	None	14.2	6.5
0.353	0.121	Yes	30	None	10.3	16.8
0.353	0.025	No	30	25	4.7	18.8
0.353	0.121	No	30	25	3.5	25.8
0.353	0.025	Yes	30	25	14.1	6.9
0.353	0.121	Yes	30	25	10.1	17.8

Conclusions

To improve the match between wind/solar energy systems and irrigation energy requirement, it is better to combine a winter crop (e.g. winter wheat) with a summer crop (e.g. corn or cotton) rather than growing just a winter or summer crop. Of all of the locations in the Great Plains where significant irrigation occurs, the two locations where a wind, solar, or wind/solar energy hybrid system would work best are southwestern Kansas and the Texas northern High Plains due to a significant amount of irrigated winter wheat grown at these locations, as well as 1000s of ha of irrigated summer crops. Solar-PV systems are a very good match to irrigation energy requirements of a combination winter and a summer crop grown in the Texas northern High Plains. A single-axis tracking system should reduce the size of the solar-PV array for irrigation and will be cost effective as long as the expense of the motorized tracking system (both installed and operation and maintenance) does not significantly affect the overall cost of the system. Upgrading from a single-axis solar-PV tracking system to a dual-axis solar-PV system will not improve economics because of the high water requirement of corn in July unless the excess energy in winter can be used for other energy requirements on the farm. The minimum price per kW of wind turbine manufacturers surveyed was ~$3,000/kW while the minimum for solar PV was $5,000/kW (non tracking). At the average 2009 price of electricity for irrigation in Texas ($0.10/kWh), a payback period of 7.5 years (10.5% IRR) was possible for wind turbines without federal incentives if the surplus electricity could be used for other on-farm uses and no loan was required. Solar PV arrays were not economically competitive with wind turbines for high volume water pumping requirements because of their higher price and lower capacity factor (e.g. requires larger power rating to provide the irrigation power requirement). With incentives (30% Federal Tax Credit and 25% USDA REAP grant), the payback period could be reduced to 4 years (21% IRR) for wind turbines, again if the surplus electricity could be used for other on-farm uses and no loan was required. At the current low field price of natural gas for irrigation $0.159/m^3 ($4.5/mcf), the only payback period under 10 years occurred when no loan was needed and with substantial federal incentives (55%). However, if the natural gas price reaches $0.282/m^3 ($8/mcf), that is equivalent to the average 2009 price of electricity for irrigation in Texas ($0.10/kWh) and the above payback periods and IRR's estimated for electricity are applicable. The PV module efficiency was assumed to be 14% (e.g. PV module at standard test conditions temperature of 25°C), but if the PV efficiency could be improved to level of well-designed wind turbines (~40%); the PV array power rating could be about one-third the size, and if cost/kW did not increase significantly, PV systems could possibly be more economical than wind turbines for crop irrigation in the Texas Panhandle.

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