Developing a Hybrid Solar/Wind Powered Irrigation System for Crops in the Great Plains

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ABSTRACT

Some small scale irrigation systems (< 2 ha) powered by wind or solar do not require subsidies, but this paper discusses ways to achieve an economical renewable energy powered center pivot irrigation system for crops in the Great Plains. By adding a solar-PV array together with a wind turbine and partitioning the center pivot irrigation system between a winter crop and a summer crop, the goal of a cost competitive large scale irrigation system powered by renewable energy may be attainable. Adding on-farm uses for the excess wind and solar energy during the winter months to produce valuable products on the farm enhances the prospects of a profitable system.

1. INTRODUCTION

Much of the crops grown in the U.S. are grown in the Great Plains (www.unl.edu/plains/about/map.shtml). In order to grow these crops or increase their yield in this region, water is pumped from underground aquifers for irrigating. The energy used for pumping the water is either fossil fuels or is energy predominantly derived from them (e.g. electricity from 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, farmers need to begin switching from a finite resource (i.e. fossil fuels like natural gas and diesel) to renewable resources (i.e. like wind, solar, and 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), so farmers may need to switch over to renewable energy in the not-to-distant future in order to continue farming, and providing the U.S. with a food supply.

Scientists at the USDA-Agricultural Research Service Conservation and Production Research Laboratory (CPRL) near Bushland, Texas and the Alternative Energy Institute,

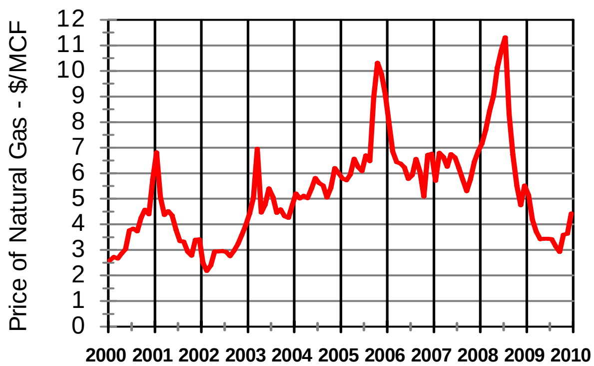

Fig. 1. Price of Natural Gas in U.S. (IEA).

West Texas A&M University, Canyon, Texas began investigating the use of wind energy to pump water for irrigation 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 not be cost effective primarily because irrigation is needed only a part of the year (1). In 2000, it was found that irrigating a citrus orchard in the Rio Grande Valley was closer to being economical for a 10 kW wind turbine due to a good matching of irrigation water required and wind energy available, and the fact that the citrus orchard used irrigation water the entire year (2). 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 concerned with high natural gas prices that limited their capacity to irrigate. Again the economics of using wind energy for irrigation were marginal at best (3). In 2006-2007 wind-assisted irrigation for the Texas northern High Plains and southwestern Kansas was studied by Texas AgriLife Extension Service. The economics were found to be marginal due to a mismatch of the irrigation energy

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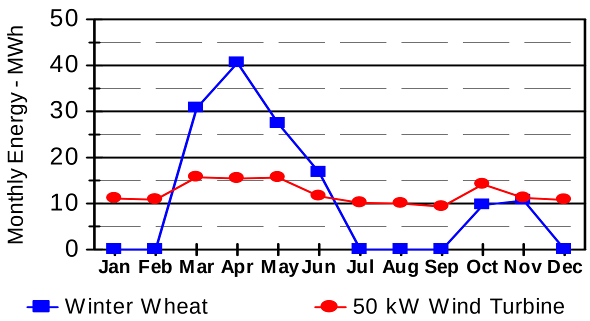
requirement and available wind resources. In addition, it was noted that utilities were resistant to purchasing wind generated electricity at more than a few cents per kWh during periods when irrigation was not performed (4). The CPRL renewable energy team has started a 5-year project plan in which one of the goals is to develop a renewable energy system for large scale crop irrigation that will also be cost competitive with current fuel choices.

2. DISCUSSION

2.1 Improving the match between irrigation energy required and renewable energy generated.

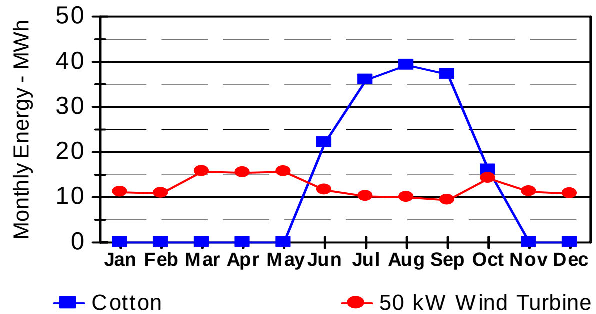
In 2004, a 50 kW wind turbine manufacturer asked the renewable energy team at CPRL to investigate the use of their wind turbine for pumping water for irrigation in the Texas High Plains. During this analysis, one of the most important advancements in renewable energy powered crop irrigation was discovered. The discovery was how 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 (i.e. qualitatively though not quantitatively) to wind turbine energy since maximum wind turbine energy occurs in spring when highest irrigation requirement occurs and minimum wind turbine energy in summer coincides with no irrigation requirement (Fig. 2).



Note: Texas Panhandle, Center Pivot, assume 1 acre-inch requires 62 kWh of energy.

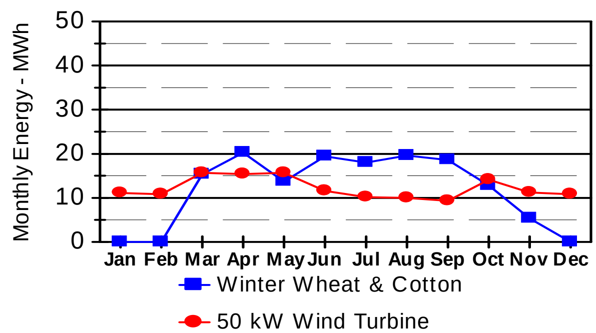
Fig. 2. Irrigating Winter Wheat (51 ha) with a 50 kW Wind Turbine (25 m hub ht.).

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 lowest (Fig. 3). 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. 4). The deficiency in wind energy in the summer in Fig. 4 implied that adding solar energy would improve the match to the irrigation energy required. This hypothesis was confirmed when the wind and solar energy available were compared to the irrigation requirement of crops in the Texas High Plains (Fig. 5). The wind energy data shown were collected north of Amarillo, Texas at a 25 m hub height (1995-1999). The solar energy shown was the average global irradiance at Amarillo, Texas from 1961 to 1990. The irrigation required for the various crops was based on 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 though no irrigation requirement shown in Fig. 2 and Fig. 4 during these months. This is because additional water is usually needed for winter wheat during winter, but can not be applied by irrigation system due to freezing conditions.



Note: Texas Panhandle, Center Pivot, assume 1 acre-inch requires 62 kWh of energy.

Fig. 3. Irrigating Cotton (51 ha) with a 50 kW Wind Turbine (25 m hub ht.).



Note: Texas Panhandle, Center Pivot, assume 1 acre-inch requires 62 kWh of energy.

Fig. 4. Irrigating Winter Wheat (25.5 ha) & Cotton (25.5 ha) with a 50 kW Wind Turbine (25 m hub ht.).

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2.2 Irrigation in the Great Plains

The qualitative amount of irrigated acreage in the U.S. can be seen in Fig. 6 (www.nass.usda.gov). In terms of the Great Plains, the highest irrigated acreage is in Nebraska, Kansas, the northern and southern High Plains of Texas, and eastern Colorado. The quantitative amount of irrigation can be seen in Fig. 7 during the period from 2000 to 2009 for the high irrigation states in the Great Plains. Nebraska has the highest amount of irrigated acreage followed by Kansas, Texas northern High Plains, Texas southern High Plains, and finally eastern Colorado.

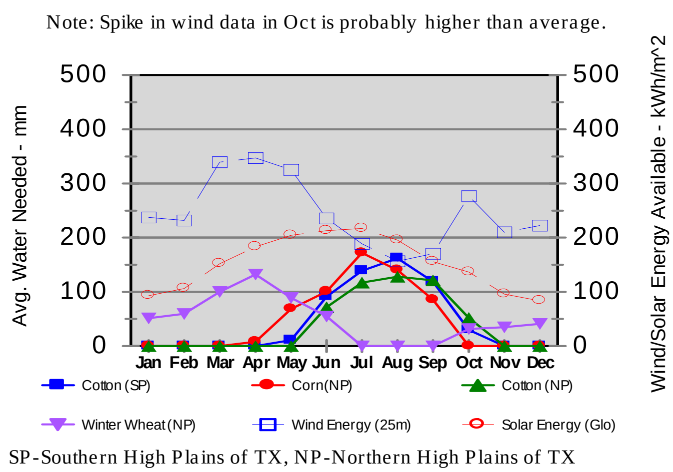

Fig. 5. Average Irrigation Water Required & Wind/Solar Energy Available (TX).

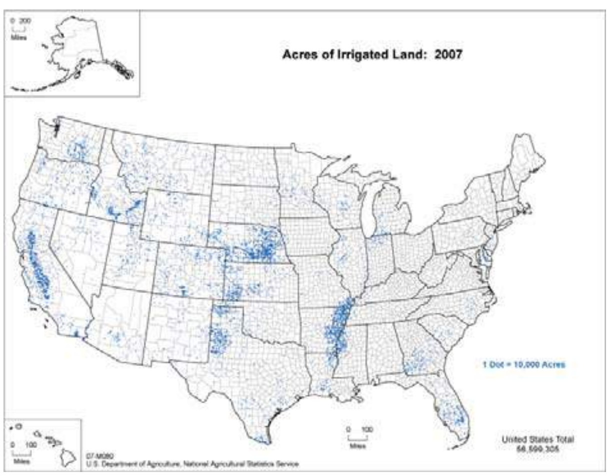

Fig. 6. Irrigated Land in U.S. (USDA-NASS,2007).

However, as was discussed in paragraph 2.1, growing both a winter and a summer crop is important to improving the match between renewable energy generated and irrigation energy required. The amount of winter wheat that was irrigated in the high irrigation states in the Great Plains can be seen in Fig. 8. Kansas and the Texas northern High Plains have the largest amount of irrigated winter wheat in the Great Plains. Although southwestern Kansas probably would be a good candidate for using renewable energy to pump water for irrigation, knowledge of the wind/solar resource, evapotranspiration (ET) required for crops, and the rainfall average for the Texas northern High Plains resulted in the analysis for this paper 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 Fig. 9.

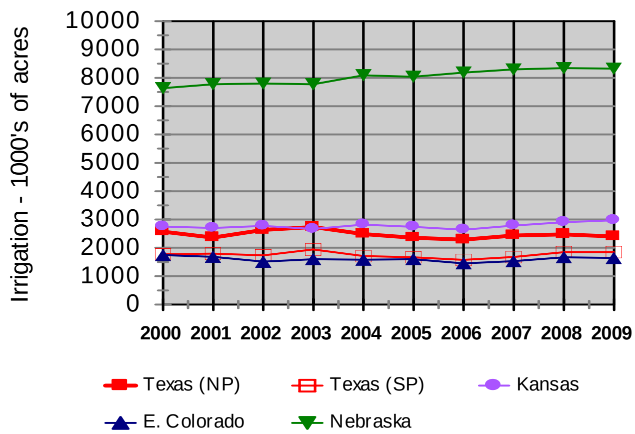

Fig. 7. Total Irrigated Acres of Crops (1 hectare = 2.471 acres), USDA-NASS.

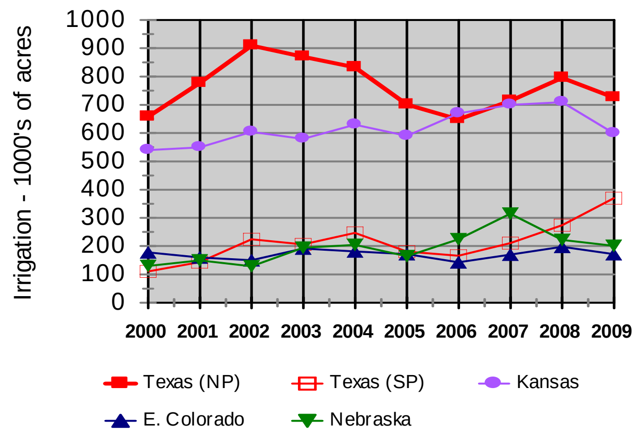

Fig. 8. Irrigated Acres of Winter Wheat (1 hectare = 2.471 acres), USDA-NASS.

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.

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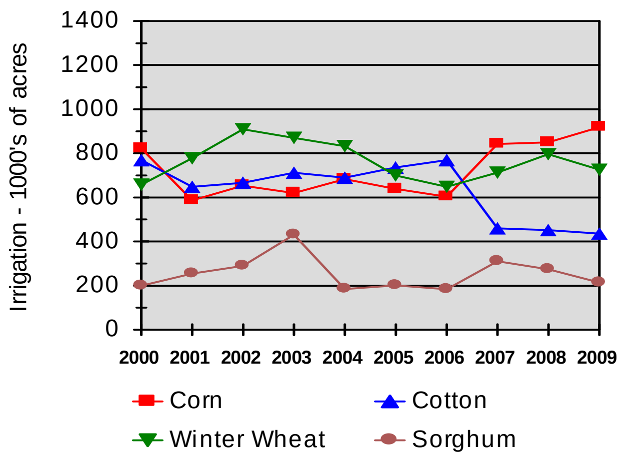

Fig. 9. Irrigated Crops in the Texas northern High Plains (1 ha = 2.471 ac), USDA-NASS.

2.3 Using solar and wind energy for irrigation in the Texas northern High Plains.

Because corn and winter wheat are currently the greatest irrigated acreages in the Texas northern High Plains, this analysis will concentrate on how well solar and wind energy generation matches the irrigation energy requirement of these two crops when grown in equal amounts on a center pivot quarter section (51 ha). The solar resource data used were collected in Amarillo, Texas (16 km east of CPRL) over the period 1961-90 (5). The wind speed data used in the analysis were gathered 24 km NE of CPRL at 25 and 40 m heights over a three-year period (1995-1997). The irrigation water required was based on the average evapotranspiration (ET) of corn and winter wheat at CPRL minus the average rainfall at Bushland over the period 1983 to 2009. Also, it was assumed that the amount of energy required to pump 1 ac-in. of irrigation water was 62 kWh (6).

How well the irrigation energy demand of corn and winter wheat on a quarter section center pivot irrigation system (51 ha) can be met by three different solar PV arrays is presented in Fig. 10. For the PV arrays, the solar cell efficiency was assumed to be 14% (e.g. crystalline PV modules) at standard temperature conditions (STC) which is 25^{o}C. The inverter efficiency was assumed to be 95% --see link www.gosolarcalifornia.ca.gov/equipment/inverter.php. The temperature of PV modules for each month had previously been measured at CPRL (7), and using those average module temperatures and assuming a 0.5% decrease in performance for each Celsius degree increase in PV module temperature, temperature sensitivity was estimated. The other efficiencies of PV system were same as assumed in on-line computer program (www.pvwatts.org) and this efficiency was 83.6%. For the first case the modules were assumed to be fixed at 20^{o} – as an aside, peak energy requirement for corn occurs in July when the optimum PV array tilt angle is about 18^{o}. 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^{o} 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 Fig. 10 that solar energy is a good match to irrigating winter wheat and corn in the Texas northern High Plains.

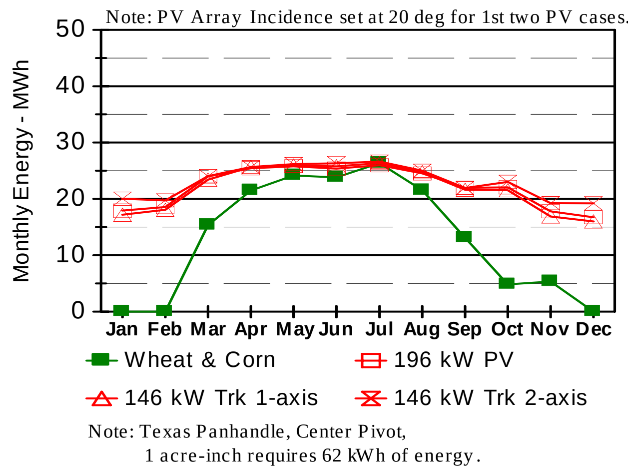

Fig. 10. Irrigating Wheat & Corn (51 ha) with Solar-PV Arrays.

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 Fig. 11. The power curve used was measured at CPRL for a 50 kW Atlantic Orient Corp.[1] (AOC) wind turbine and was corrected to sea level standard day conditions. The AOC is no longer in business but a similar wind turbine is being manufactured by Atlantic Orient Canada Inc. For each month the wind turbine energy was calculated based on average wind distribution, power curve, average air density at CPRL, and an availability of 90%. In order to meet the high irrigation water requirement in July, a wind turbine rated at 150 kW (no wind turbine available at this power currently) is required or could be met by either a 100 kW wind turbine (Northern Power Systems has a wind turbine rated at 100 kW) combined with one 50 kW turbine or three wind turbines rated each at 50 kW – if three wind turbines,

[1] Mention of trade names or commercial products in this report is solely for the purpose of providing specific information and does not imply recommendation or endorsement by the U.S. Department of Agriculture.

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they could be located at three corners of center pivot and should not significantly interfere with each other. Increasing the hub height of the wind turbine from 25 m to 40 m did not significantly increase the energy of the wind turbine in July. 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, and their energy output should be 50% more than at a 25 m height, but the cost of tall tower likely would be too expensive for this size wind turbine. Comparing Fig. 10 and Fig. 11, it is obvious that solar is a better match to the irrigation energy requirement than wind.

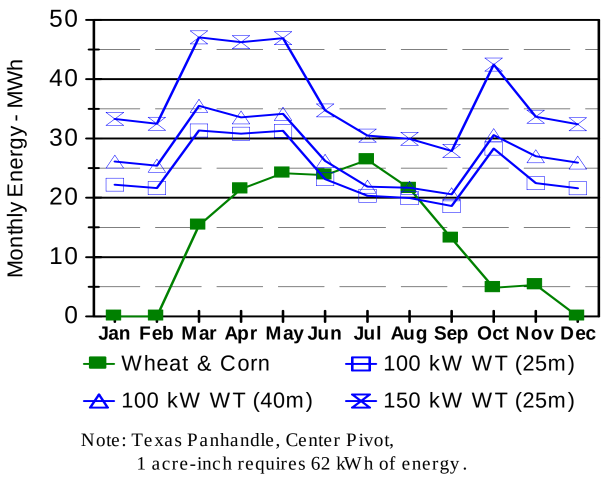

Fig. 11. Irrigating Wheat & Corn (51 ha) with Wind Turbine(s).

Two cases of combining solar-PV arrays with a 50 kW wind turbine are depicted in Fig. 12 which again was to meet the irrigation energy requirement for a quarter section center pivot of winter wheat and corn. The first case is for a fixed PV array at 20^o 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. An advantage of hybrid wind/solar systems is that reliability is improved since irrigation system is not as dependent on whether the sun is shining or the wind is blowing on a particular day.

For all the wind, solar, and hybrid wind/solar systems shown in this analysis, 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 may be 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, the types of energy that power the irrigation systems are natural gas, diesel, and utility supplied electricity – approximately 1/3rd for each. 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 on the farm 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 (8). 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, a new engine would need to be purchased to operate on biodiesel. The irrigation systems connected to a utility could also use that available energy as a backup.

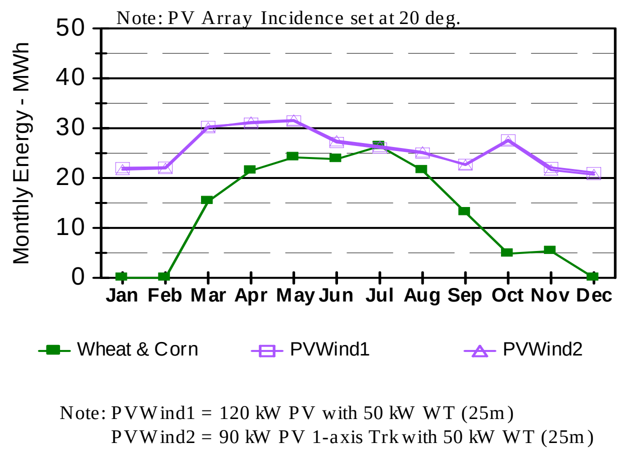

Fig. 12. Irrigating Wheat & Corn (51 ha) with PV Array and Wind Turbine.

2.4 Greenhouse powered by wind energy in winter and other uses of excess wind/solar energy generated

Since no irrigation is performed during winter months (December, January, and February) all the electricity generated by the wind energy system is available. Hourly wind speed data were collected at a 25 m height at CPRL during the winter of 2008-2009, and with the hourly air temperature data at CPRL, an analysis was performed to estimate on how large a greenhouse that grew tomatoes could be to use excess wind energy for heating. Assumptions for the greenhouse were:

1. Only 1/3rd of solar radiation is transferred to the ground
2. The greenhouse is semi-cylindrical made of 2 layers of plastic with an air gap between the layers.
3. The heat coefficient. = 0.7 Btu/(hr ft^2 ^{o}F)

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4. Maintain a temperature of at least 15^{o}C inside the greenhouse.

The diurnal comparison of greenhouse energy required for heating versus energy generated by a 50 kW wind turbine at 25 m height can be seen in Fig. 13. The size greenhouse that could be powered by excess wind energy was only 6 m by 12 m (e.g. width x length). If a solar-PV/wind hybrid system is 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 would be released at night when heat most needed.

Although greenhouses in this preliminary calculation do not appear to be a good use of excess renewable energy, there are 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 to be used to power farm machinery. The excess renewable energy electricity could also be used in production of hydrogen through electrolysis which could be used in fuel cells if fuel cells become economical to power farm machinery.

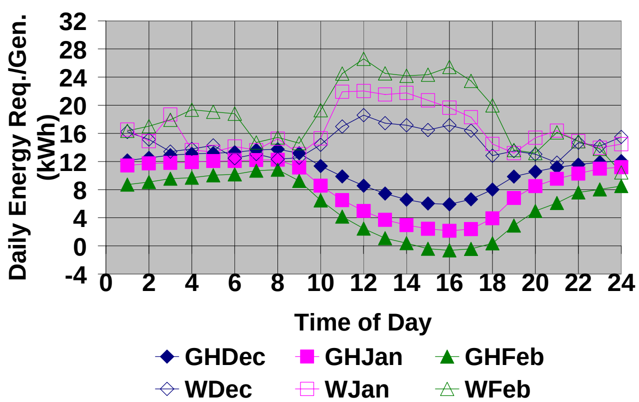

Fig. 13. Greenhouse Energy Required Vs. 50 kW Wind Turbine Energy Generated (Winter,CPRL,2008-2009).

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 utilities (IOUs) and cooperatives in the Texas northern High Plains have resisted buying back the excess wind/solar electricity at a retail price. IOU's will usually only pay avoided cost or fuel adjustment cost which is only a few cents per kWh for excess electricity generated but sometimes require demand charges which usually cancel out any money made from sale of excess renewable energy. Cooperatives in the Texas northern High Plains area usually don't pay anything for excess generated renewable energy electricity.

3. 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 grow just a winter or summer crop. Of all the locations in the Great Plains where significant irrigation occurs, the two locations where a wind or 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 – in addition, to 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 as long as the expense and reliability of motorized tracking system is not significantly effected. 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 PV module efficiency was assumed to be 14% (e.g. at STC), but if the PV efficiency could be improved to level of well-designed wind turbines (~40%); the PV array size could be about 1/3rd the size.

4. ACKNOWLEDGEMENTS

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