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ENERGY CONSERVATION USING VARIABLE-FREQUENCY DRIVES FOR CENTER PIVOT IRRIGATION

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OPPORTUNITIES TO REDUCE ELECTRIC PUMPING ENERGY USE

One factor that influences the energy use by electrically power irrigation pumps is the pressure required to deliver water through center pivots operating on undulating terrain. Other factors include the condition of the pumping plant resulting from improper pump selection or pump adjustment, impeller wear, or improperly sized engines and motors. However, since a major part of the U.S. irrigated farm area is on ungraded surfaces with varying slopes, engineering design specifications can affect overall energy use rates. Design specifications call for supplying water at a design flow rate and pressure at the point of highest field elevation with all sprinklers operating. This design ensures uniform water distribution along the pivot for the “worst case” scenario. The pump impeller is selected that operates at its peak efficiency at the design flow rate (gpm) and required pump outlet pressure (psi). The pump impeller typically operates at constant speed of rotation (rpm).

For center pivots operated on undulating terrain, as the pivot moves downhill away from the highest field elevation, the required pumping pressure decreases and the excess pressure builds up in the delivery pipeline while pressure regulators maintain the design pressure to each sprinkler. Adjustment of the pump speed to reflect the pressure required in real-time could conserve a significant amount of energy for many field installations.

PRESSURE ADJUSTMENTS USING VFDS

Pump manufacturers typically provide impeller performance curves for different impeller diameters at an impeller speed of 1760 rpm. By installing or stacking multiple impellers in series and altering the impeller diameter or speed, one impeller design can supply water to s with widely different flow rate and pressure requirements. One way to change the impeller speed powered by electric motors is to use a monitor and control system similar to a variable frequency drive (VFD).

To conserve energy, the design and operation of the VFD must minimize motor speed under conditions when the pump is inefficient. Change in pump speed result from the ratio of the adjusted frequency delivered by the VFD to the frequency delivered by the power supplier. For example, use of a VFD to decrease the frequency supplied to an electric motor from 60 to 50 Hz will reduce the motor speed from 1760 to 1467 rpm ((50/60) x 1760 rpm).

Factors to consider include are VFD efficiency, maintenance costs, expected life, and capital expense. Though typical VFD operating efficiencies are in the 95% to 98% range (USDA-NRCS, 2010), the combination of an electric motor with VFD lowers the system operating efficiency to approximately 92%. Recent VFD cost estimates average approximately $250 per kilowatt and average power use is approximately 60 kilowatts for a total cost of approximately $15,000 per installation.

One very important consideration for VFDs is that incoming alternating current is converted to direct current and then back to alternating current at the desired frequency. The process sometimes referred to as chopping the direct current to create alternating current involves rapid switch on-off cycles to create a square wave power rather than the smooth sinusoidal wave. Delivery and use of the square wave power requires a specially designed electric motor and failure to install the appropriate motor will greatly reduce the lifetime of the motor.

The payback period depends on the usage of the irrigation system, which can vary nationwide from 500 to 2500 h per year depending on the geographic location and annual climatic conditions. In Nebraska, long-term average irrigation system operating times for a pivot length of 1300 feet vary from 500 to 1000 hours per year based on the long-term average net irrigation required for a corn and a water application efficiency of 85% (NDNR, 2006).

STUDY OBJECTIVES

With advances in satellite imagery, digital elevation models (DEMs) are available to determine the impact of topography with much greater precision. DEMs maps available in a 10 m $\times$ 10 m grid are appropriate for displaying the continuously changing topographic surface and are widely used for elevation analysis (Thompson et al., 2001). These DEMs become inputs to geographic information system (GIS) based tools to study the elevation differences that occur in a particular field as the center pivot rotates.

The specific objective of this project was to develop and apply a model to simulate the energy conservation achieved when using a VFD to alter the operating pressure for center pivots with various corner attachments based on elevation data obtained from DEM maps.

MATERIALS AND METHODS

STUDY AREA

The study used center pivot irrigated fields located in ten counties of Nebraska as shown in Figure 1 (CALMIT, 2005). The counties selected exhibited differences in field topography, a range of annual operating hours, and had a large number of full-sized center pivot systems. One hundred (100) center pivot systems were randomly selected from each county for the analysis (1000 field sites).

FIELD DATA

The project used field elevations for 10 m grid datasets from the USGS National Elevation Dataset (USGS, n.d.) and center pivot locations from the University of Nebraska-Lincoln Center for Advanced Land Management Information Technologies online dataset (CALMIT, 2005). The DEMs and center pivot datasets were imported into GIS software (ArcGIS 10.2, ESRI, Redlands, CA.). The county boundary dataset was obtained from the Geospatial Data Gateway provided by the USDA-NRCS. Figure 2 depicts a field with elevation contours and a 7-tower center pivot superimposed on the image. The towers of the pivot traverse an area where the field elevation varies from 1587 feet to 1649 feet (62 feet change).

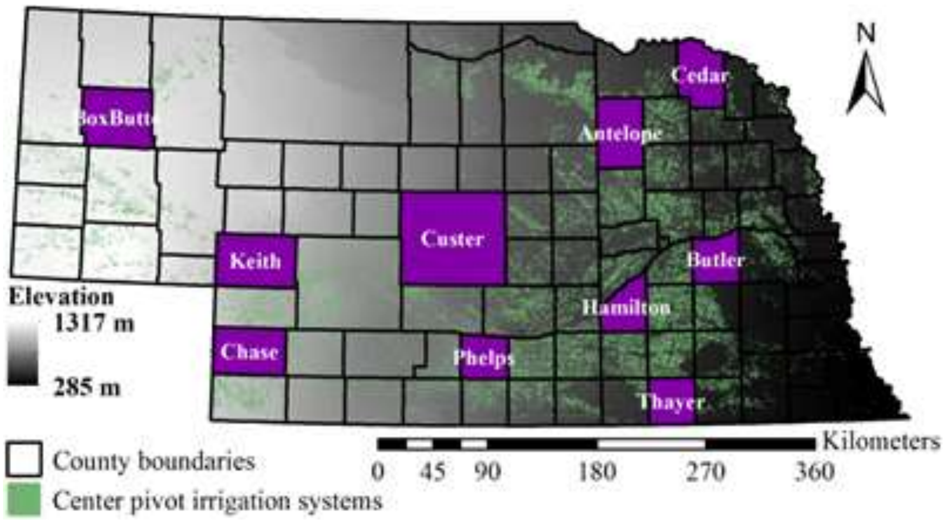

Figure 1. Locations of the ten study counties with center pivot fields, with a shade of gray elevation map of Nebraska in the background.

For each scenario discussed below, two approaches were evaluated to determine differences in energy use: 1) Approach 1 was for a typical design at constant motor speed; and 2) Approach 2 with motor speed adjusted to supply the minimum system pressure requirements.

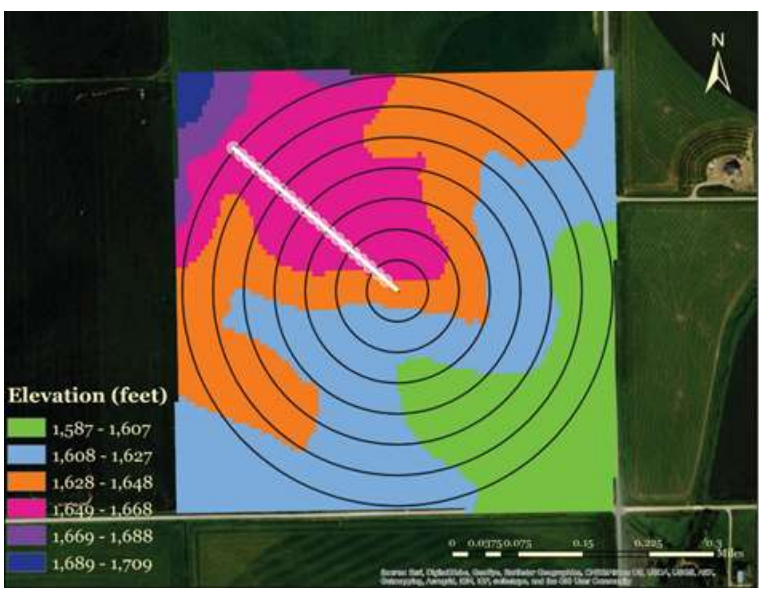

Figure 2. Demonstration of the irrigation system tower paths along with the range in elevation in each color band.

Scenario 1

Figure 3 depicts a standard irrigation system with no end gun for one quarter of a revolution.

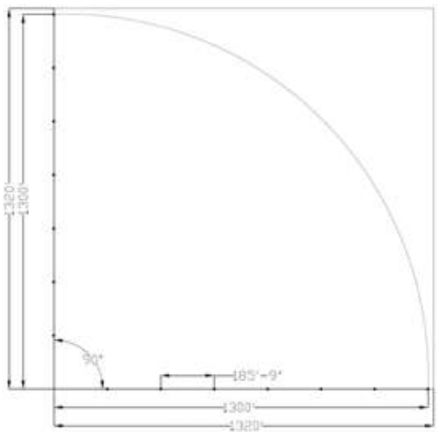

Figure 3. Quarter section of the field showing movement of a system in Scenario 1. (No attachments)

Several assumptions were necessary in order to represent the majority of irrigation systems available in Nebraska and to simplify the computational procedure. All the systems selected were standard installations that made a full circle and the pivot point located at or near the center of a square 160-acre field. A constant number of sprinklers attached to the top of the pivot lateral (no drop tubes). The remaining assumptions made in this scenario were as presented in Table 1.

Table 1. Assumptions made in Scenario 1.

Radius of field	1300 ft
Number of towers	7
Distance between adjacent towers	185.7 ft
Area irrigated	121 acres
Minimum pressure requirement at each sprinkler	30 psi
Pressure regulator requirement	5 psi
Diameter of pipe lateral	6.3 in
Riser height of the pivot	11 ft
System flow rate	780 gpm
Motor efficiency	88%
Pump efficiency	83%
VFD efficiency	96%

A graphical comparison between Approach 1 where a constant pressure was supplied to the pivot point and Approach 2 where a VFD was employed to supply the exact pressure required by all sprinklers on the pivot is presented in Figure 4. The difference in pivot point pressure at each angular position was used to calculate energy savings achieved by Approach 2. **Note:** Approach 1 results in a horizontal line based on fully operational pressure regulators and the 'worse case' scenario design. Where the two lines intersect is the position of the greatest field elevation and thus the greatest pressure requirement.

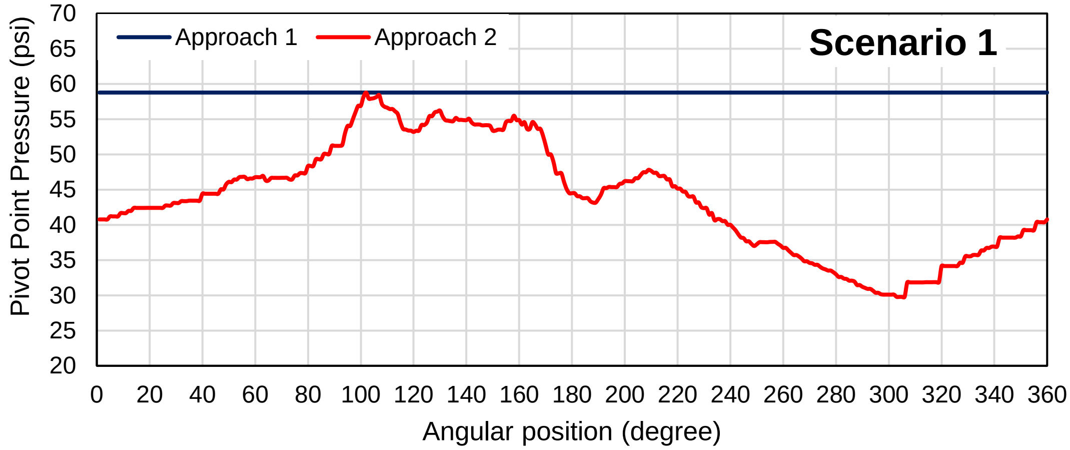

Figure 4. Graphical comparison between Approach 1 and Approach 2 for Scenario 1.

Scenario 2

Figure 5 presents the Scenario 2 where all systems included an end gun at the end of the lateral. The end gun selected was a Nelson 100 Series Big gun with nozzle size of 0.8 inch. Table 2 presents other assumptions for this scenario. Use of the endgun increased the area irrigated to around 133 acres.

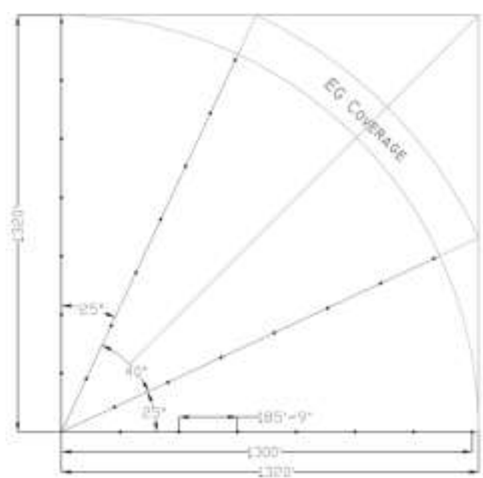

Figure 5. Quarter section of a field showing movement of a system and activation of an endgun in Scenario 2.

Table 2. Assumptions made in Scenario 2.

Area irrigated	133 acres
Pump type selected	Goulds 12CMO
Diameter of pump impeller	8.67 in.
Design flow rate	950 gpm
Minimum pressure requirement at each sprinkler	30 psi
Pressure regulator requirement	5 psi
Diameter of pipe lateral	6.3 in
Riser height of the pivot	11 ft
Nozzle size of end gun	0.8 in.
End gun actuation angle in each corner	40°
Catalogue radius at 60 psi	140 ft
Effective radius at 60 psi	121 ft
Motor efficiency	88%
VFD efficiency	96%

Figure 6 presents a graphical comparison between Approach 1 where the pressure supplied to the pivot point remained constant until endgun activation and Approach 2 where a VFD control system supplied the exact pressure required by the center pivot.

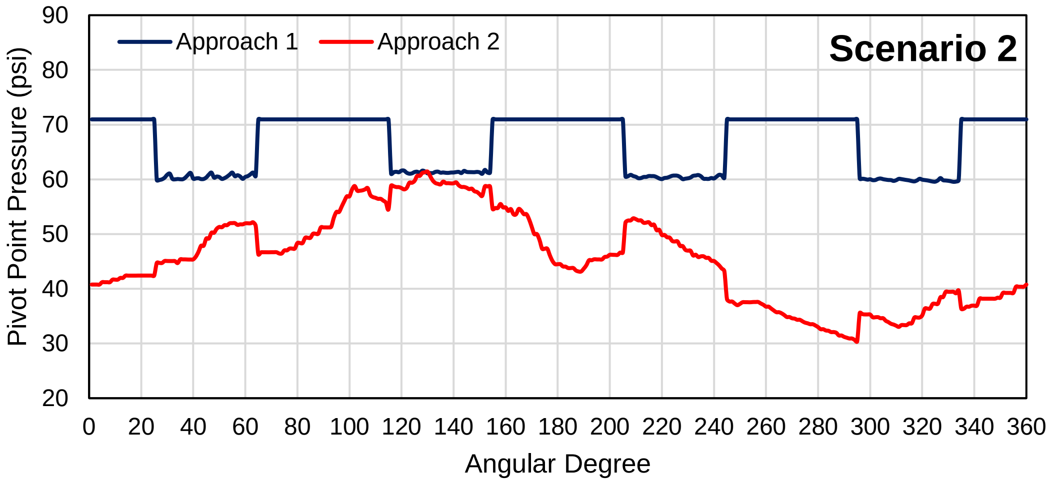

Figure 6. Graphical comparison between Approach 1 and Approach 2 for Scenario 2.

Scenario 3

In this scenario, systems were equipped with corner extension at the end of the lateral. Figure 7 depicts a quarter of a revolution and an indication where the corner extension is fully activated.

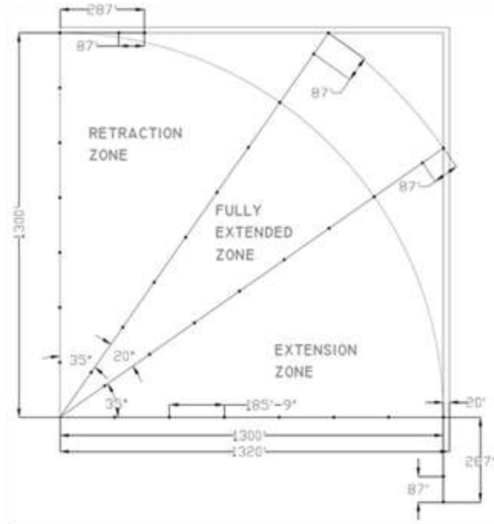

Figure 7. Quarter section of the field showing movement of a center pivot and the fully active area of a corner extension in Scenario 3.

The corner extension used was a Valley precision corner with total length of 287 feet including a 200 feet long span and 87 feet overhang with pipe diameter of 6.625 inch. In every quarter section of the field, the corner extension traveled through three zones: extension zone from 0° to 35°, fully extended zone from 36° to 55° and retraction zone from 56° to 90° (Figure 7). Use of the corner extension increased the area irrigated by 15 acres to 148 acres when compared to Scenario 2. Table 3 presents additional assumptions for this scenario.

Table 3. Assumptions made in Scenario 3.

Area irrigated	148 acres
Pump type selected	Gould's 12RJHO
Diameter of pump impeller	8.0 in
Design flow rate	1110 gpm
Length of corner extension	287 ft
Flow rate range in corner extension	0 - 380 gpm
Minimum pressure requirement at each sprinkler	30 psi
Pressure regulator requirement	5 psi
Diameter of pipe lateral	6.3 in
Riser height of the pivot	11 ft
Nozzle size of end gun	0.8 in.
End gun actuation angle in each corner	40°
Catalogue radius at 60 psi	140 ft
Effective radius at 60 psi	121 ft
Motor efficiency	88%
VFD efficiency	96%

Figure 8 presents a graphical comparison between Approach 1 where the pressure supplied to the pivot point was held constant until the corner extension became activated and Approach 2 where a VFD was employed to supply the exact pressure required by the center pivot pressure.

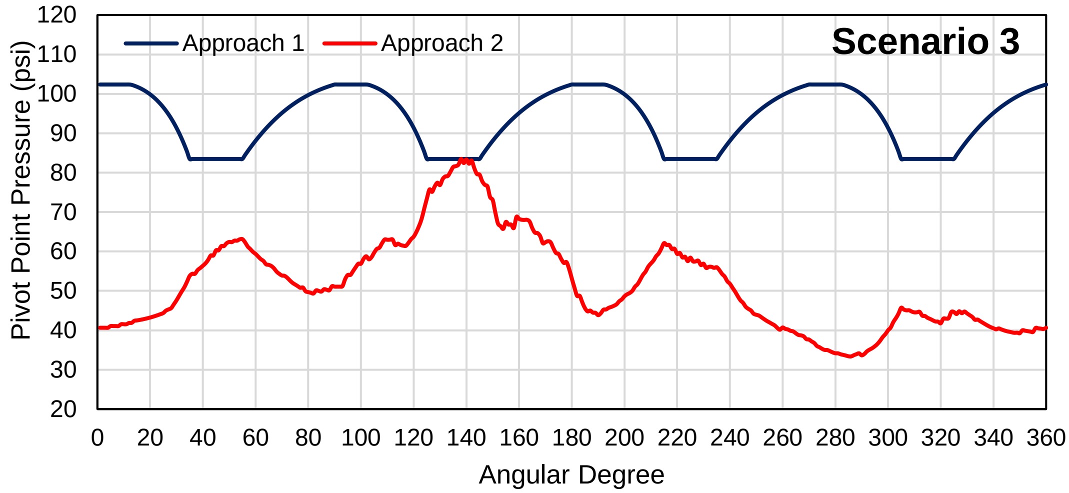

Figure 8. Graphical comparison between Approach 1 and Approach 2 for Scenario 3. Gradual change in pressure indicative of additional sprinklers being activated or shut off.

Scenario 4

Figure 9 presents a scenario with an endgun attached to an end of the corner extension described in Scenario 3. The figure shows that the endgun is active for 9 degrees in each corner.

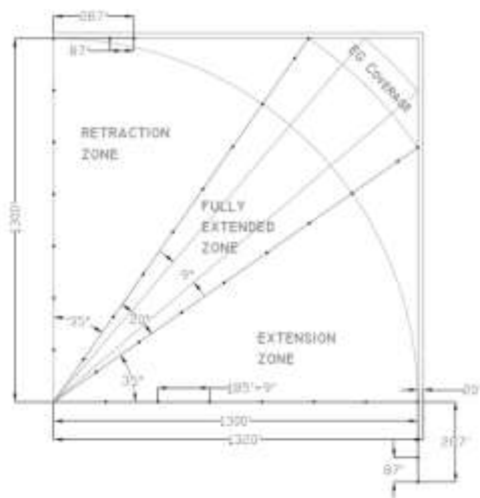

Figure 9. Quarter section of the field showing movement of the system with a corner attachment and endgun operational in Scenario 4.

Due to the location of the endgun at the end of the corner extension, a 0.9 inch straight-bore nozzle was used from the Nelson Big Gun 100 Series. Addition of the end gun and corner extension increased the irrigated acres to 152 acres and Table 4 presents other assumptions used in the model.

Table 4. Assumptions for Scenario 4.

Area irrigated	152 acres
Pump type selected	Gould's 13CHC
Diameter of pump impeller	9.17 in
Design flow rate	1350 gpm
Nozzle size of end gun	0.9 in
End gun actuation angle in each corner	9°
Catalogue radius at 60 psi	147 ft
Effective radius at 60 psi	125 ft
Minimum pressure requirement at each sprinkler	30 psi
Pressure regulator requirement	5 psi
Diameter of pipe lateral	6.3 in
Riser height of the pivot	11 ft
Nozzle size of end gun	0.8 in.
End gun actuation angle in each corner	40°
Catalogue radius at 60 psi	140 ft
Effective radius at 60 psi	121 ft
Motor efficiency	88%
VFD efficiency	96%

Figure 10 presents a graphical comparison between Approach 1 where the pressure supplied to the pivot point was held constant until the corner extension and endgun became activated and Approach 2 where a VFD control system supplied the exact pressure required by the center pivot sprinklers.

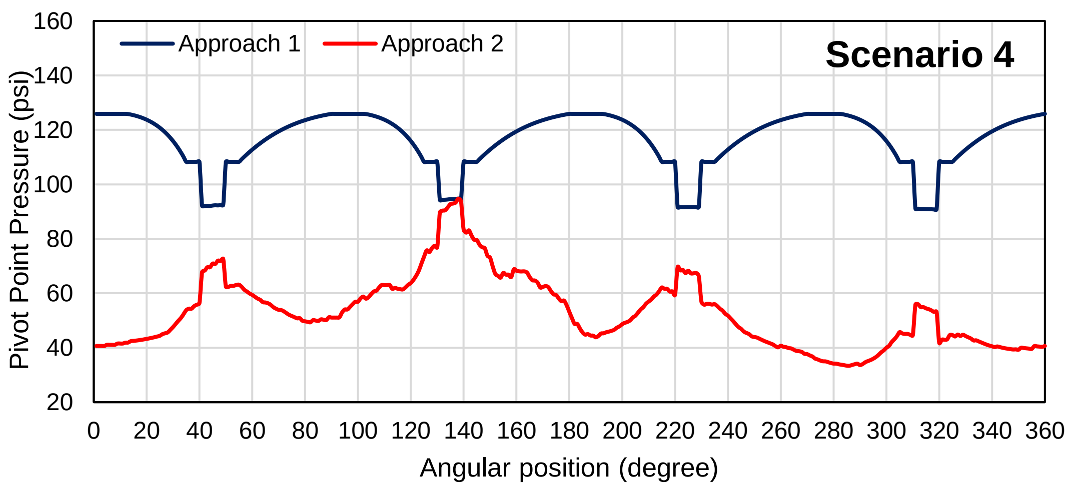

Figure 10. Graphical comparison between Approach 1 and Approach 2 for Scenario 4. Change in pressure indicative of when the corner extension becomes and endgun becomes activated.

RESULTS

MEAN DESIGN PRESSURE

The maximum design pressure required for 1000 center pivots averaged across all counties for Scenarios 1-4 was calculated using Approach 1. As expected, the design pressure increased from Scenario 1 to Scenario 4 in all ten counties (Table 5). The increasing design pressures with each scenario was due to the increase in flow rate required to irrigate the additional acres associated with each corner attachment. The increased flow rate led to greater friction losses than for the scenario without attachments. The elevation at the last corner extension tower may also have increased design pressure in Scenario 3 and 4.

Table 5. Maximum design pressure (psi) required using Approach 1 for Scenarios 1-4.

	Mean Pivot Pressure (PSI)			
County	**Scenario 1 (Standard Pivot)**	**Scenario 2 Pivot w/ Endgun**	**Scenario 3 Pivot w/Corner Extension**	**Scenario 4 Pivot w/Corner Extension +Endgun**
Antelope	57	62	74	84
Box Butte	52	57	69	80
Butler	50	55	67	78
Cedar	64	67	80	89
Chase	51	56	68	79
Custer	63	67	81	90
Hamilton	50	55	67	78
Keith	53	57	70	80
Phelps	51	55	67	78
Thayer	51	56	68	79
Overall Average	**54**	**59**	**71**	**81**

Overall, the increase in mean design pressure increased by over 5 psi by attaching an end gun to a standard system (Table 5, Scenario 2). The pressure increased by an additional 12 psi with the attachment of a corner extension (Table 5, Scenario 3). With a corner extension and end gun (Scenario 4), the pivot point pressure increased to 81 psi. In total, the addition of corner attachments led to an increase in average required pump outlet pressure of 27 psi or a 50% increase above the standard center pivot without an endgun.

MEAN ENERGY SAVINGS

The long-term net irrigation requirement for each county is presented in Table 6. On average, each system applied 10.3 inches of water and the operating characteristics of the different corner attachments depicted in Figures 3, 5, 7 and 9 resulted in estimated energy savings per hour of operation between Approach 1 and Approach 2 that are provided in Table 6. Following the trend in pressure requirement the hourly cost savings averaged $0.21, $0.70, $1.61, and $3.02 per hour for 1000 center pivots installed using Scenarios 1, 2, 3, and 4, respectively.

The question remains whether the savings will pay for the VFD installation. Ultimately, it is the number of hours each system operates that will determine whether the savings will be sufficient to pay for the VFD installation costs. A Series Present Worth Factor is needed to estimate an annual cost savings based on a specific loan duration and interest rate or rate of return. If one assumes a

15-year loan at 7% interest, the Present Worth Factor is 9.11. On average, if the VFD cost is \$15,000, the potential annual energy cost savings for a center pivot would need to be \$1647 per year (\$15,000 ÷ 9.11). Based on the average savings of \$3.02 per hour for a center pivot with a corner extension and endgun (Scenario 4 in Table 6), the system would need to operate in excess of 545 hours (\$1647 ÷ \$3.02 per hour). As the savings per hour decreases, the number of hours of operation must increase to pay for the VFD.

Table 6. Summary of annual hours of operation and potential energy cost savings by using a VFD on different center pivot configurations.

County	Net Irrigation	Average Savings per Pivot $/hour			
		Scenario Number			
	Inches	1	2	3	4
Antelope	8.9	0.34	0.84	1.8	3.19
Box Butte	14	0.15	0.65	1.52	2.94
Butler	7.3	0.04	0.50	1.38	2.81
Cedar	8.5	0.58	1.10	2.09	3.46
Chase	13.3	0.07	0.55	1.45	2.87
Custer	11.2	0.50	1.03	2.05	3.38
Hamilton	8.4	0.03	0.50	1.35	2.79
Keith	13.3	0.18	0.66	1.56	2.99
Phelps	10.5	0.08	0.55	1.42	2.84
Thayer	7.7	0.10	0.58	1.44	2.88
Average	**10.3**	**0.21**	**0.70**	**1.61**	**3.02**

Net Irrigation from Nebraska LB962 report
85% water application efficiency
Electric power cost = \$0.11 per kWh
Scenario 1 is a standard system without an endgun
Scenario 2 is a standard system with an endgun
Scenario 3 is a system with a corner extension
Scenario 4 is a system with a corner extension + and endgun

Two things to note in Table 6: 1) Fields without a major change if system flow rate will not generate enough savings to pay for the VFD; and 2) Systems with corner extensions and endguns will likely generate enough energy savings to pay for the VFD installation regardless of where the system is located in the High Plains.

POSITION OF THE PRESSUE SENSOR

Installation of pressure sensor somewhere on the distribution system is part of every VFD monitor and control system. The pressure sensor position is important because the VFD adjusts the power frequency and thus motor speed to maintain a set pipeline pressure at the pressure sensor location. The most convenient location is near a pivot tower due to transmitting the pressure value back to the pump site through the pivot power cable. The previous discussion was based on placement of the sensor at the optimum tower on the system. Sensors placed at the pump outlet are convenient to install and maintain, but that position is often the worst location for the sensor on fields with topography. In our work, the best pressure sensor location was near tower 8 or the last tower on about 50% of the fields studied (Table 7). For 20% of the systems, the best location was near tower 7 and for 15% it was near tower 6. In some fields the pivot point is at the highest elevation in the field so even Tower 1 was the best location. This suggests that to obtain all of the potential energy savings the location of the control sensor should be determined on a field-by-field basis.

Table 7. Summary of the best location of the pressure sensor for 1000 center pivots in Nebraska.

	Percentage of Angular Positions						
County	Tower 1	Tower 2	Tower 3	Tower 4	Tower 5	Tower 6	Tower 7
Antelope	2.3%	3.2%	6.0%	10.9%	17.3%	16.1%	44.3%
Box Butte	0.5%	0.5%	3.5%	6.7%	18.5%	19.1%	51.2%
Butler	0.4%	0.8%	1.9%	4.6%	12.8%	23.8%	55.8%
Cedar	7.6%	7.8%	9.8%	12.4%	13.3%	12.8%	36.3%
Chase	0.5%	0.7%	2.0%	4.6%	15.2%	21.2%	55.8%
Custer	2.3%	2.5%	4.9%	7.7%	13.4%	17.9%	51.3%
Hamilton	0.2%	1.5%	1.9%	5.6%	15.7%	26.5%	48.7%
Keith	2.7%	2.0%	3.6%	6.9%	15.7%	16.8%	52.3%
Phelps	0.8%	1.0%	2.5%	5.5%	15.0%	24.3%	50.9%
Thayer	1.8%	1.8%	4.0%	7.7%	16.8%	27.1%	40.9%
Overall	**1.9%**	**2.2%**	**4.0%**	**7.3%**	**15.4%**	**20.5%**	**48.7%**

Conclusions

Use of a VFD will help maintain pressure delivered to center pivots at the level required at all locations in the field. It will also help respond to changes in pumping water level that occur in season and over the lifetime of the installation. However, our study of over 1000 center pivot sites in Nebraska suggests that the energy savings will not produce sufficient economic returns to pay for the VFD installation on standard systems without corner attachments or fields with low elevation changes. On average, an installation would need to reduce energy costs by at least $1,647 per year to pay for the VFD over a 15-year period and 7% interest rate. Results suggest that, depending on the hours of operation, only systems with corner extensions and endguns will consistently generate sufficient energy savings to pay for the installation. One factor what we did not include in this evaluation was the potential economic return associated with maintaining water application uniformity on center pivots operating with unpredictable changes in pumping water levels during a growing season. A relatively low reduction in sprinkler pressure could result in yield losses that may make the VFD economical on a broader range of field sites.

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