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ENERGY CONSERVATION USING VARIABLE FREQUENCY DRIVES FOR CENTER PIVOT IRRIGATION SYSTEMS

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INTRODUCTION

Center pivot irrigation systems are highly efficient and the most widely used irrigation systems in Nebraska. However, the power unit used to supply water to each center pivot could be operated more efficiently in terms of energy use. Center pivot systems are designed to operate on a broad range of topographic variation and operating pressures. To supply all areas of a field with a uniform water application, engineering design specifications call for meeting the design flow rate and pressure at the point of greatest field elevation with all sprinklers engaged. This is done regardless of how much of the irrigated area requires that specific design specification. Consequently, the combination of engineering design and topographic variation may result in pumping pressures that are greater than necessary for some portion of a field. Adjustment of pressure and flow rate in real-time could conserve a significant amount of energy.

Adjustment of pivot point pressure can be accomplished by varying the speed of the power supply. For electric motors, using a variable frequency drive (VFD) to monitor and control motor speed is an option. Similar monitor and control systems are available for internal combustion engines but can only be used when the engines are not equipped with electric power generators.

A VFD was used in the evaluation of energy conservation for four different center pivot system Scenarios or configurations as explained below:

1. **Standard center pivot system with seven towers and without an end gun**. *For this Scenario the required flow rate and pressure remains constant for the entire revolution.*
2. **Standard center pivot system with seven towers and equipped with an end gun**. *Typical end guns operate for 40^o in each corner or 44% of each revolution.*
3. **Standard center pivot system with seven towers and equipped with a corner extension**. Typical corner extension *operate for 20^o in each corner or 22% of each revolution.*
4. **Standard center pivot system with seven towers and equipped with a corner extension and an end gun**. *Typical end guns on corner extensions operate for 9^o in each corner or 10% of each revolution.*

PROCEDURES

Ten counties in Nebraska were selected based upon differences in field topography and the number of center pivot irrigation systems in the county. Figure 1 presents the counties of interest on Nebraska map with elevation map in the background.

One hundred center pivot systems were randomly selected from each county for the analysis (total of 1000 field sites). A center pivot system was overlain on each field site with equal distance between the towers and calculations were conducted thereafter based on drive wheel travel.

All fields that met two field conditions were filtered out of the potential sites in each county:

1. System makes a complete circle.
2. Pivot lateral length must be 1300-1320 ft.

In each county 100 center pivot fields were randomly selected from the pool of potential pivots.

Different parameters were assumed for each Scenario, however the basic calculations were the same. One basic assumption was that all systems were equipped with functioning pressure regulators which assured that the flow rate and pressure was maintained at all times. End guns did not include pressure regulators. Thus, any changes in pressure would impact the end gun flow rate.

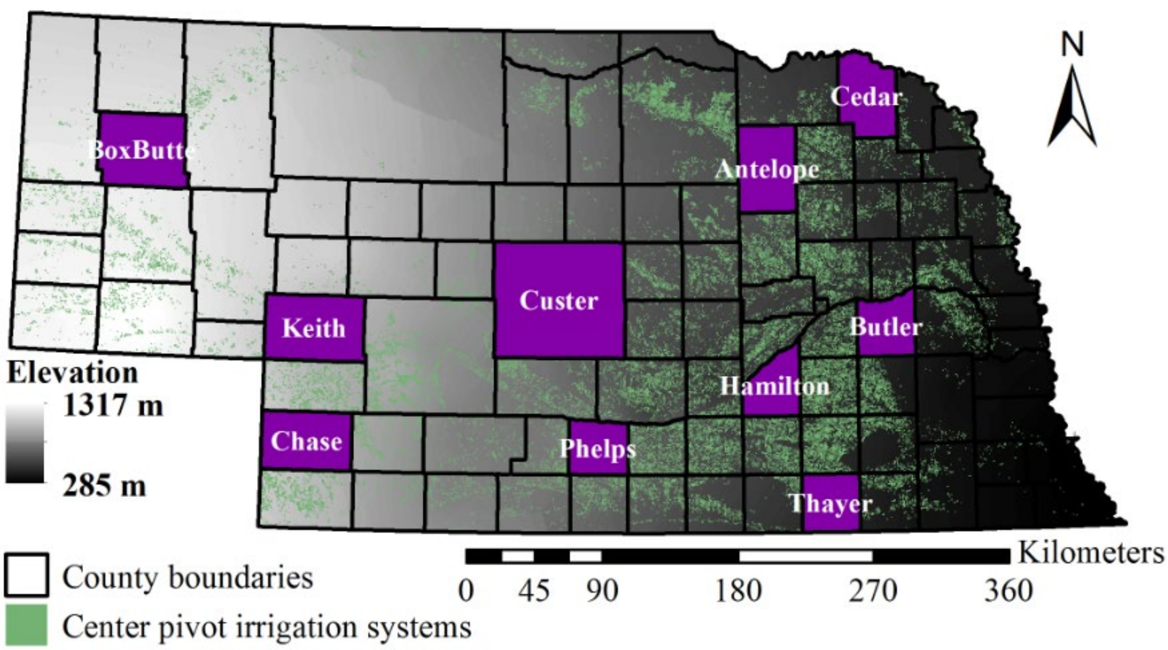

Figure 1. Locations of the 10 study counties with the center pivot fields (green dots) and elevation map of Nebraska in the background.

Two approaches were used to determine the energy conservation that could result by using a VFD to control the electric motor speed of rotation.

Approach 1 was to maintain a constant irrigation motor/pump speed. The design pressure for this approach is the pressure required at pivot point to deliver water to the last sprinkler at highest elevation in the field. The pressure required includes pipeline friction losses, elevation changes, pressure regulator requirement, and sprinkler operating pressure. Figure 2 depicts the design pressure of 59 psi for an example field using Approach 1 which remains constant for each position of the pivot rotation. This is true despite elevation changes because of the operating pressure regulators on each sprinkler.

Approach 2 uses a VFD to adjust the motor and pump speed to match the pivot pressure needed at each degree of rotation. The design pressure was calculated at each degree of rotation and adjusted according to the elevation of the last sprinkler. The white italic font in Figure 2 represents the required pivot point pressure at nine different locations of a center pivot rotation.

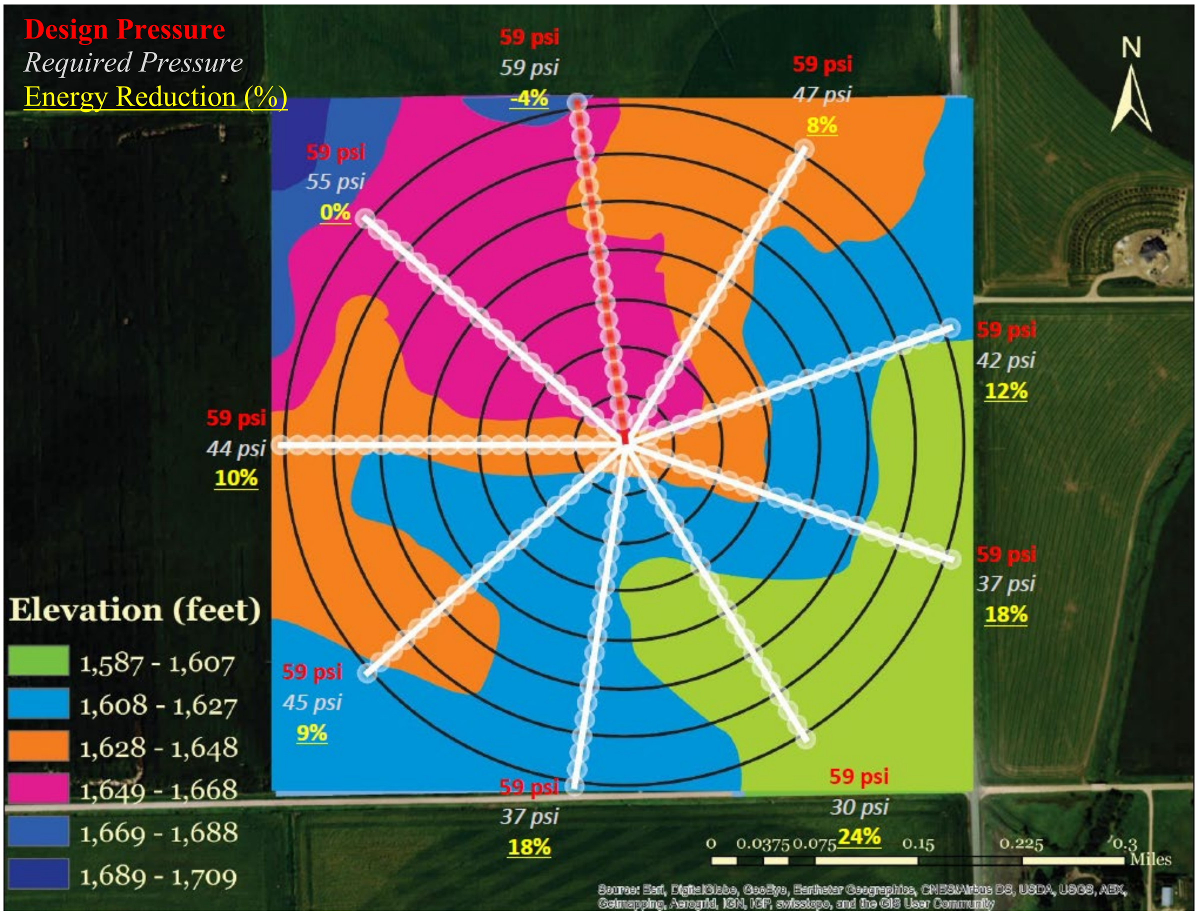

Figure 2. Design pressure (red), required pressure (white), and the percentage of energy reduction (yellow) by the reducing the pump speed is presented for nine positions of the field. The center pivot in red color (upward to the left of center) represents the design location which is the highest elevation in the field.

PUMPING PLANT PERFORMANCE PARAMETERS

Total dynamic head (TDH) is the sum of the discharge head and the lift from the water surface in the well bore to the point where discharge pressure is measured at the pump outlet. It is the total equivalent depth from where the water is pumped, taking column, pipe and other friction losses into account as shown in Equation 1. All units are in feet of head.

$$TDH = Total\ Loss + H_o \tag{1}$$

$$Total\ Loss = elev + lift + friction + riserh$$

Where:

$elev$ = the maximum elevation above the pump outlet reached by the pivot pipeline, ft.
$lift$ = the distance between the pumping water level and the pump outlet, ft.
$friction$ = the friction loss within the column pipe, delivery pipe and pivot lateral, ft.
$riserh$ = the height of pivot lateral above the ground surface, ft., and
H_o = the pressure required at each sprinkler inlet, ft.

Pumping lift values are different for each field and it is difficult to obtain accurate pumping lift from public information sources. To simplify the procedure an average pumping lift value was retrieved from Nebraska Department of Natural Resources (NDNR, 2015) for each county. That lift was used to evaluate the energy conservation potential for 100 center pivots from each county.

The elevation map used was 33 ft × 33 ft raster retrieved from United States Geological Survey-National Elevation Dataset (USGS, 2015). Field elevations for each tower were recorded in one degree of rotation increments for each field site (360 locations).

Friction loss within the lateral pipeline was calculated using Chu and Moe equation (Chu and Moe, 1972) and Dercas (Valiantzas and Dercas, 2005) which is based on the Hazen-Williams equation.

Riser height is the height the pivot mainline above the ground. We used an 11 foot riser height in this study.

Minimum regulator pressure (H_o) is the pressure required at each sprinkler before the regulator. Including the regulator pressure requirement of 5 psi, a minimum of 35 psi of pressure was required at the pressure regulator inlet.

Other losses: Due to different field installations, the friction within the pump column and the velocity head loss were considered to be negligible. The addition of these two sources of pressure loss would not have changed the outcome of this analysis.

Design pivot point pressure was determined by calculating the maximum required pivot point pressure for the highest elevation in each field as shown in Equation 2. This design pressure was fixed for the complete pivot rotation.

$$DPPP = Max.(RPPP_{1\text{-}360}) \tag{2}$$

Where:

$DPPP$ = Design Pivot Point Pressure (psi).

Required pivot point pressure was calculated at each degree by adding the maximum loss from all the seven towers to the minimum sprinkler pressure as shown in Equation 3.

$$RPPP_{1\text{-}360} = R_{sp} + R_r + (0.434 \times Max.\ (HL_{1\text{-}7})\ ) \quad (3)$$

Where:

$RPPP_{1\text{-}360}$	= Required Pivot Point Pressure (psi)
R_{sp}	= minimum sprinkler pressure (30 psi)
R_r	= regulator requirement (5 psi)
$Max.\ (HL_{1\text{-}7})$	= maximum total head loss (ft) for towers 1 to 7 at each degree.

Water Horsepower (WHP) was calculated using TDH and flowrate (Q) as shown in Equation 4.

$$WHP = \frac{Q \times TDH}{K_o} \quad (4)$$

Where

WHP	= water horsepower (hp)
Q	= flow rate (gpm)
TDH	= total dynamic head (feet)
K_o	= 3960, units conversion coefficient

Brake Horsepower (BHP) was calculated using WHP and an estimate of the pumping plant efficiency P_e (including motor (88%) and pump (83%) efficiency) as shown in Equation 5. The VFD efficiency of 96% was included in pumping plant efficiency for Approach 2.

$$BHP = \frac{WHP}{P_e} \quad (5)$$

Energy reduction: The percentage of energy reduction was calculated comparing the use of brake horsepower in both the approaches for each degree of rotation as shown in Equation 6.

$$Energy\ reduction(\%) = \frac{avg.[BHP_{1\text{-}360}(Approach\ 1)\text{-}BHP_{1\text{-}360}(Approach\ 2)]}{avg.\ BHP_{1\text{-}360}\ (Approach\ 1)} \times 100 \quad (6)$$

Using both Approaches, an example of single field with all the four scenarios is depicted in Figure 3. The design pressure shown in blue dotted color (Approach 1) remains constant throughout the rotation in Scenario 1 whereas it changes in other scenarios due to fluctuation of flowrate resulting from the on/off setting for an end gun and/or corner extension. The required pressure at each degree is shown in red dot color (Approach 2) and is the minimum pressure required at that particular degree of rotation to meet the pressure requirements along the lateral at that position in the field.

The pressure difference between Approach 1 and Approach 2 is the unrequired pivot point pressure in the system that can be reduced using a VFD monitor and control system. When the corner extension and/or end gun turns off, a greater amount of unrequired pressure is built up in the system (Scenario 2, 3, and 4 in Figure 3) due to shifting of the operating point on the pump performance curve to the left.

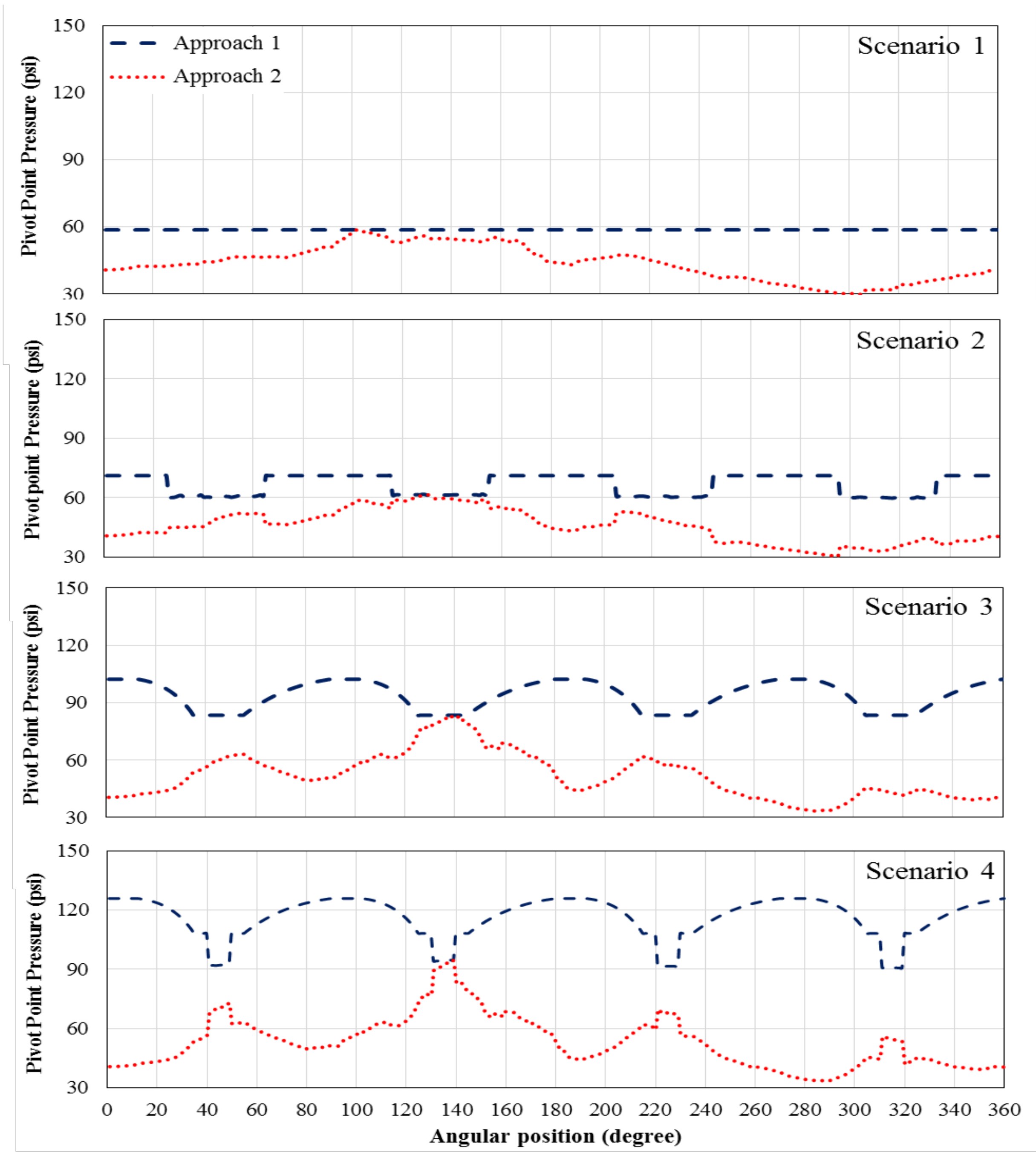

Figure 3. Graphical comparison between Approach 1 where the pressure supplied to the pivot point was held constant and Approach 2 where a VFD was employed to adjust the pump speed to supply the pressure required by all sprinklers on the center pivot. The difference in pivot point pressure at each angular position was used to calculate energy savings achieved by Approach 2. ***Note:*** *Scenario 1 (no end gun); Scenario 2 (with end gun); Scenario 3 (with corner extension); and Scenario 4 (with corner extension and end gun).*

Table 1. Average elevation difference in the study counties and average energy reduction (%) in all four scenarios.

		Average Energy Reduction (%)[1]			
County	**Average Elevation Difference (ft)[2]**	**Scenario 1**	**Scenario 2**	**Scenario 3**	**Scenario 4**
Antelope	29.5	5.1%	12.0%	19.0%	29.0%
Box Butte	17.1	1.3%	8.0%	15.0%	26.0%
Butler	11.8	0.2%	8.0%	17.0%	29.0%
Cedar	**44.6**	**9.6%**	**16.0%**	**23.0%**	**32.0%**
Chase	14.1	0.6%	8.0%	17.0%	28.0%
Custer	44.3	6.9%	13.0%	20.0%	29.0%
Hamilton	**11.5**	**0.0%**	**8.0%**	**16.0%**	**28.0%**
Keith	18.7	1.9%	9.0%	16.0%	26.0%
Phelps	13.5	0.9%	8.0%	17.0%	28.0%
Thayer	13.8	1.3%	9.0%	17.0%	28.0%

[1] Average potential energy savings when using a VFD to alter pump speed
Scenario 1: Standard center pivot systems with seven towers without an end gun.
Scenario 2: Standard center pivot system with an end gun.
Scenario 3: Standard center pivot system with a corner extension.
Scenario 4: Standard center pivot system with a corner extension and an end gun.

[2] Average difference between pivot point elevation and the greatest field elevation.

RESULTS

The varying topography within each field played a major role in level of energy conservation in the form of pressure reduction. The counties with the greatest elevation differences (Cedar, Custer, and Antelope) conserved more energy than counties with flat topography (Hamilton, Butler, and Chase) for Scenario 1. The energy use reduction increases when other factors like pump performance curve as corner attachments are added in Scenario 2, 3 and 4. The average energy reduction in all four scenarios along with average elevation difference for each of the 10 study counties is presented in Table 1.

Minimizing the pressure supplied to each center pivot system (Approach 2) often leads to energy reduction in electricity (kWh) use. One way to evaluate the impact of using a VFD is to determine the variation in the potential energy use reduction for each Scenario. By aligning the percent energy use reduction from least to greatest and graphing the results we can determine how many installations will have greater The exceedance function for the percentage of center pivot systems and the energy reduction for the four scenarios for 10 study counties is presented in Figure 4. In Scenario 1, the results illustrate that in the counties with large in-field differences in elevation such as Cedar, Custer and Antelope, a greater percentage of center pivots could reduce energy consumption whereas in counties with less variable terrain, more than 50% of the pivots saved no energy. As corner attachments are added for Scenarios 2 to 4, the differential in flow rate increases and hence the number of fields that would benefit from the use of a VFD increases. In addition, the range of energy reductions within the county narrows (Figure 4) due to the greater impact of the corner attachments on overall energy use.

In this analysis the pressure sensor used to control motor speed, and determine the level of energy use reduction for each field, was installed at the optimum location of the system. Installing the pressure sensor at the pump outlet is the most convenient but almost always the worst location. Tower 7 was the best location in just under 49% of our field installations, Tower 6 was best for 20%, and Tower 5 was best for 15%. Thus, field topography enters this decision as some sites have the greatest elevation and pressure requirement somewhere other than at the last sprinkler. Pressure distribution calculations conducted for the sprinkler package should be helpful in deciding where to install the sensor.

The percent energy reduction can be converted into monetary terms based on the price of fuel and the depth of irrigation water applied in a particular region. Converting the percentage savings to the economic feasibility of recouping an investment was accomplished using the Series Present Worth Factor. In essence, how much could be borrowed today and paid back over a series of years with an estimated level of savings each year. For this analysis we assumed that we could borrow money for 15 years at 7% interest. The resulting Series Present Worth Factor is 9.11 so we multiply the annual savings for each system by 9.11 to get the potential investment available to install a VFD. The estimated cost for an installed VFD designed for a 60 bhp electric motor was $15,000.

Please note that use of a VFD requires a specially designed electric motor. Few motors in operation meet these design specifications. Thus, the cost of installing the VFD should include the cost of the new electric motor. Failure to install the correct electric motor will likely result in motor failure after a few hundred hours of operation.

Table 2 presents the average investments for each county in our analysis and Scenario. Cedar County exhibited one of the greatest percent savings (Table 1), however due to the number of pumping hours per year in eastern Nebraska, the potential investment is less than for counties like Keith County which resulted in a lower percentage savings but requires more irrigation water applied each year. None of the county averages were sufficient to recoup the cost of installation unless the system included a corner extension with an end gun.

It should be noted that we assumed typical operation of each of the corner attachments in all 4 corners of the field. Fields where the attachments operate for less of the revolution will not generate the same level of savings nor the investment listed in Table 2. Likewise, fields where corner attachments operate for greater portions of a circle will generate greater savings. This points to the need to evaluate each field installation to assess whether the savings would pay for the investment.

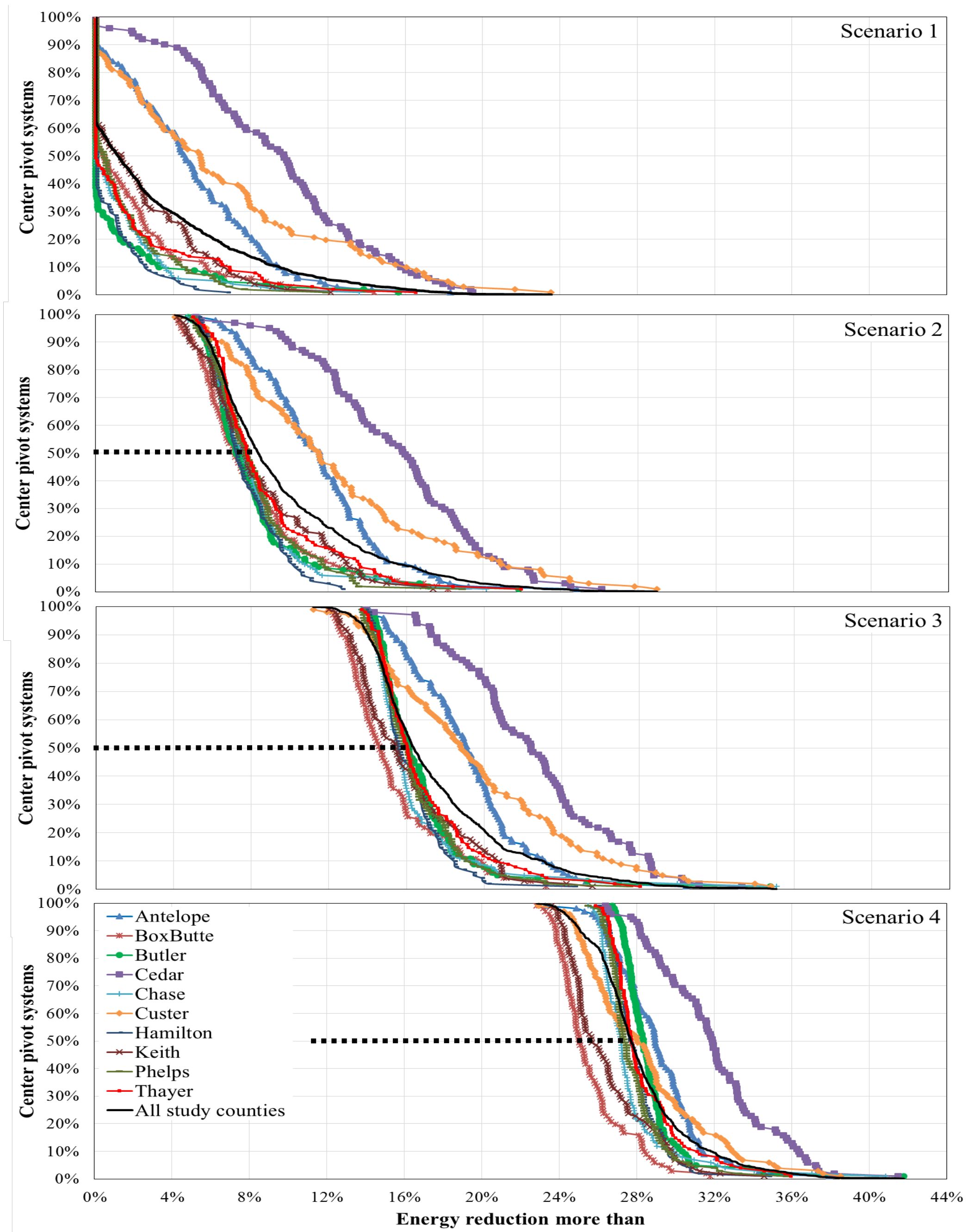

Figure 4. For each study county, the exceedance function of energy use reduction by using Approach 2 where a VFD was employed to supply the exact pressure required to meet the pressure required by all sprinklers on the center pivot. *The dotted lines indicate percentage reductions estimated for 50% or more of the fields involved in the study for each Scenario.*

SUMMARY

The use of VFD can provide significant savings in terms of energy conservation for some installations. The total capital investment that can be justified is directly related to the difference in operating pressure between a constant motor speed and variable motor speed operation. Since the price of VFD is based on the horsepower of the electric motor, systems with greater pressure and greater pumping water levels will require greater initial investments. Systems without corner extensions will likely not be able to recover the initial investment while systems with corner extensions with end guns will almost always pay for the investment. This is due to the initial design to meet flow rate and pressure requirements with all sprinklers in operation even if the last sprinkler operates for a very small portion of a revolution.

Economic Feasibility of VFD

Series Present Worth Factor: 9.11 (7% for 15 Years)

	Potential Investment ($)			
Counties	**Standard systems**	**Scenario 2 (End Gun)**	**Scenario 3 (Corner Extension)**	**Scenario 4 (Corner Extension + End gun)**
Antelope	2160	6169	13242	**23637**
Box Butte	940	7073	**17383**	**34045**
Butler	67	3017	8307	**17102**
Cedar	3900	7855	14757	**24554**
Chase	336	5888	**15832**	**31761**
Custer	4165	9492	**18959**	**31529**
Hamilton	0	3372	9357	**19496**
Keith	1235	6939	**17016**	**32946**
Phelps	420	4654	12277	**24761**
Thayer	480	3652	9162	**18433**
Average	**1360**	**5811**	**13629**	**25826**

Table 2. Average investment in a VFD monitor and control system for each county and Scenario assuming a 15-year loan at 7% interest. Average cost of installation was estimated at $15,000. *Average investment across 10 counties for each Scenario is provided in the bottom line*.

Other considerations can justify the installation of a VFD system. For example, installations where significant changes in pumping water level occur during the growing season and/or from year to year. If, due to changes in pumping water level, the pressure delivered to each sprinkler is less than design, non-uniform water distribution will occur resulting in reduced crop yields. Water application uniformity will be impacted the most near the end of the lateral which irrigates the greatest area per foot of pivot length and thus potentially have the greatest economic impact. The initial design and selection of the VFD under these circumstances must allow the motor speed to operate at greater speeds should the pumping water level increase during the season.

Installations that can justify a VFD system include center pivots that adjust the water application depths in management zones created for variable rate irrigation. For these systems, sprinklers on a portion of the pivot lateral are cycled on/off to deliver different depths of water application. Pivot manufacturers attempt to minimize the fluctuation in pivot pressure resulting from some sprinklers being cycled off through various methods. Often the operating conditions still result in excess pressure in the pipeline that is in addition to the Scenarios evaluated in the paper. Thus, VFDs are often recommended for variable rate irrigation systems.

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