ENERGY CONSERVATION USING VARIABLE FREQUENCY DRIVES FOR CENTER PIVOT IRRIGATION SYSTEMS IN NEBRASKA

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INTRODUCTION

Center pivot irrigation systems are highly efficient and the most widely used irrigation system in Nebraska. However, the power unit used to supply water to each pivot could be made more efficient in terms of energy use efficiency. Center pivot systems operate on rolling terrain and need pressure at the pivot point to supply water to the far end of the system. To supply all areas of a field with a uniform water application, engineering design specifications call for supplying water at a design flow rate and pressure at the point of greatest 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 a major portion of a field. Adjustment of pressure in real-time could conserve a significant amount of energy.

Adjustment of pivot point pressure can be done by varying the speed of the electric motor using a variable frequency drive (VFD) or a monitor and control system for an internal combustion engine. For the study described here, a VFD was used in the evaluation of energy conservation for four center pivot system scenarios:

1. Standard center pivot systems with seven towers without an end gun.
2. Standard center pivot system with seven towers equipped with an end gun.
3. Standard center pivot system with seven towers equipped with a corner extension.
4. Standard center pivot system with seven towers equipped with a corner extension and an end gun.

PROCEDURES

Ten counties were selected based upon differences in field topography and the large number of center pivot irrigation systems in that particular county. The counties selected were Antelope, Box Butte, Butler, Cedar, Chase, Custer, Hamilton, Keith, Phelps, and Thayer. Figure 1 presents the counties of interest on Nebraska map with an elevation map in the background.

One hundred center pivot systems were randomly selected from each county for the analysis (total of 1000 field sites). The center pivot irrigation systems present in Nebraska are shown in the Figure 1 below depicted by green dots. A center pivot system with equal distance between the towers was overlain on each field site and calculations were conducted thereafter based on drive wheel travel.

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

1. The pivot makes a complete circle, and
2. The pivot lateral length is in the range of 1300-1320 ft.

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.

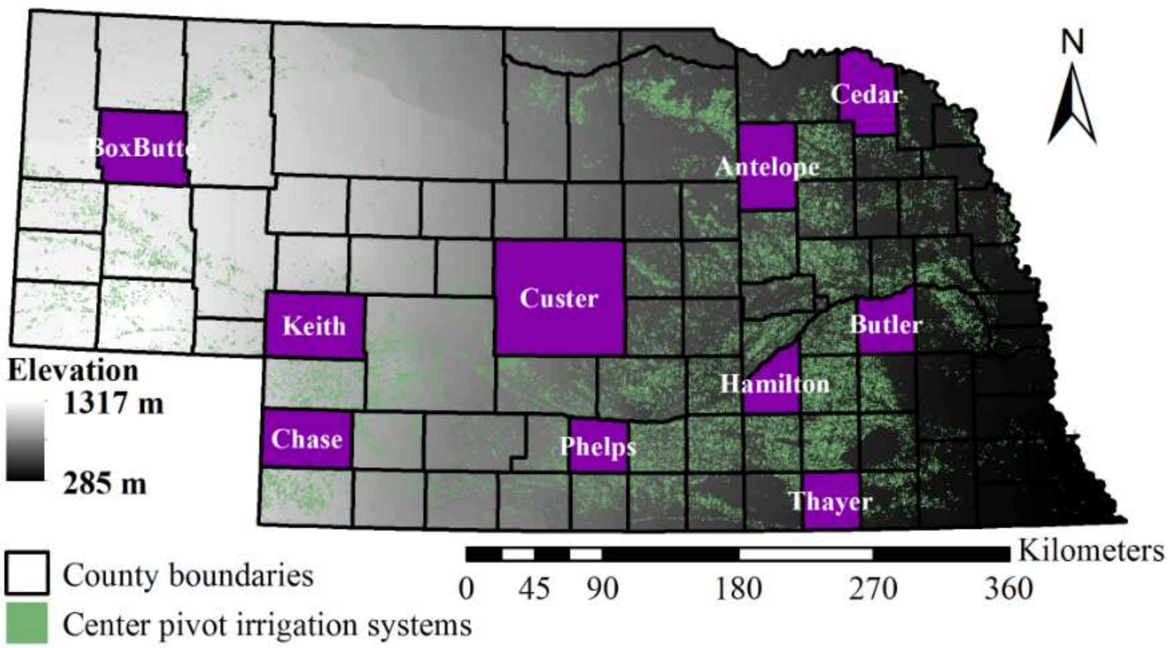

Figure 1. Locations of the 10 study counties with the center pivot fields and elevation map of Nebraska in the background.

Two approaches were used:

Approach 1 was to maintain a constant irrigation pump speed which is the traditional way of operating the pump. This design would include the necessary pressure required at pivot point to deliver water to the greatest elevation in the field. The pressure required includes pipeline friction losses, elevation differences, pressure regulator requirement, and sprinkler operating pressure. For example, the design pressure in the example field shown in Figure 2 was 59 psi was used for Approach 1 and remains constant throughout the rotation.

Approach 2 was a new technique that included use of 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 and adjusted according to the head requirements at each degree. In Figure 2, the italic font represents the required pressure at nine different locations of a center pivot rotation.

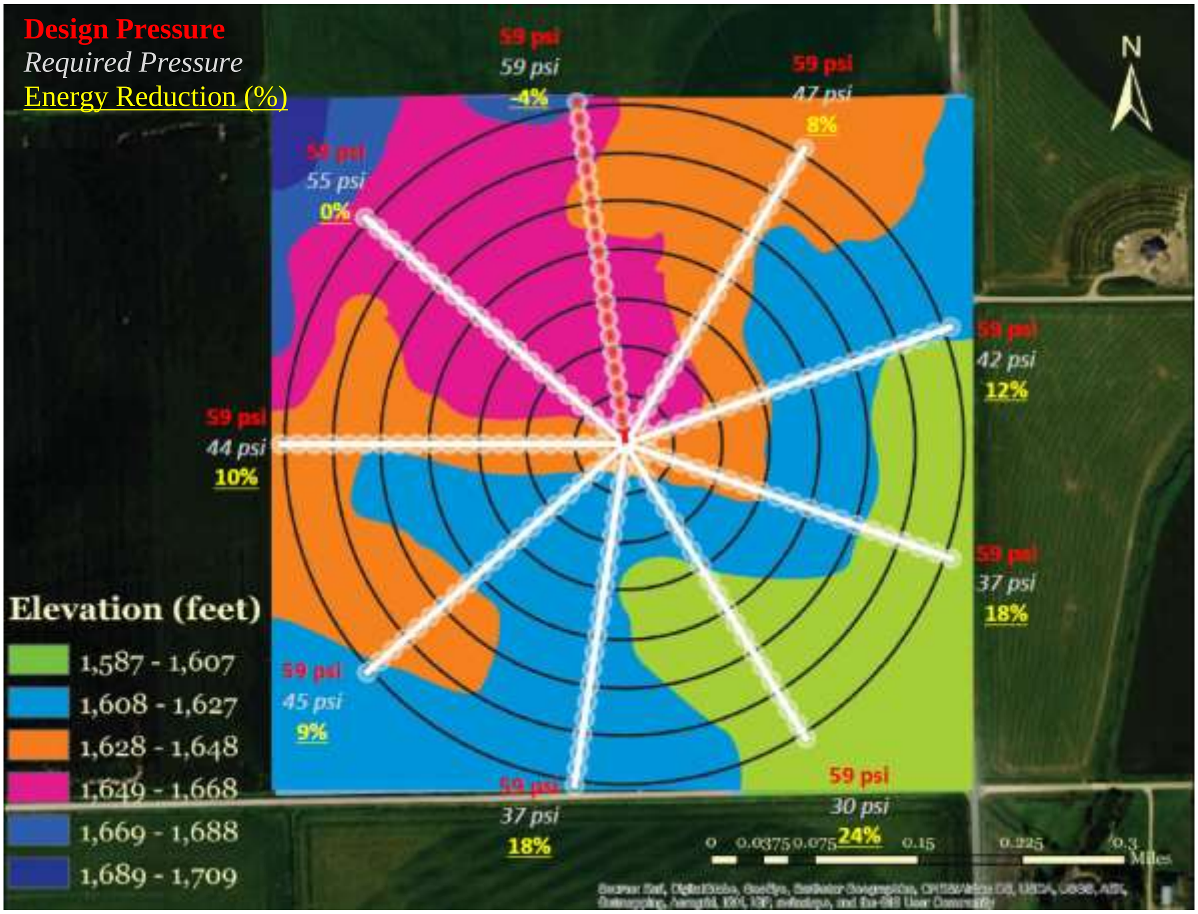

Figure 2. Center pivot irrigation system travelling in a circle along varying topography. Design pressure, required pressure and the percentage of energy reduction by reducing design pressure to required pressure is presented at nine different positions of the field. The center pivot in red color represents 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. 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.

$$TDH = Total\ Loss + H_o \qquad (1)$$

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

where

$elev$ = the maximum elevation reached by the pivot lateral 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) records for each county. That lift was used to evaluate the energy conservation potential for 100 center pivots selected 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 the Chu and Moe equation (Chu and Moe, 1972) and Valiantzas and Dercas equation (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 pressure regulator pressure requirement of 5 psi, a minimum of 35 psi of pressure was required before the pressure regulator for all the systems.

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 change the outcome of this analysis.

Design pivot point pressure was determined by calculating the maximum required pivot point pressure for the highest elevation condition 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.

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

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.

$$WHP = \frac{Q \times TDH}{K_o} \tag{4}$$

where

WHP = water horsepower (hp)
Q = flow rate (gpm)

TDH = total dynamic head (feet)
K_o = 3960

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.

$$BHP = \frac{WHP}{P_e} \tag{5}$$

Energy reduction: The percentage of energy reduction was calculated comparing the brake horsepower in both the approaches as shown in equation 6.

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

Using both approaches, an example of single field in all the four scenarios is shown in Figure 3. The design pressure for Approach 1 is depicted by the dashed line and remains constant throughout the rotation in Scenario 1 whereas it changes in other scenarios due to fluctuation of flowrate (end gun or corner arm on/off cycles). The required pressure at each degree for Approach 2 is depicted by the dotted line. This line is the minimum pivot pressure required to fulfill all the pressure requirements along the lateral at each degree of rotation. The pressure difference between Approach 1 and Approach 2 is the unrequired pivot point pressure that can be reduced using VFD. When the corner extension and end gun turns on/off, a greater amount of unrequired pressure is built up in the system (Scenario 2, 3, and 4 in Figure 3) and the pump efficiency decreases due to shifting the operating point on the pump performance curve.

RESULTS

The varying topography within the field played a major role in conserving energy in the form of pressure reduction. The counties with large elevation differences (Cedar, Custer, and Antelope) could conserve more energy than counties with flat topography (Hamilton, Butler, and Chase) in Scenario 1. The energy reduction starts increasing due to other common factors like pump performance curve as we proceed from Scenario 1 to Scenario 4. The energy reduction can be converted into monetary terms based on the price of fuel and the duration of irrigation in that particular region. The type of fuel used, fuel price and duration of pumping operation varies a lot from western to eastern Nebraska. 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.

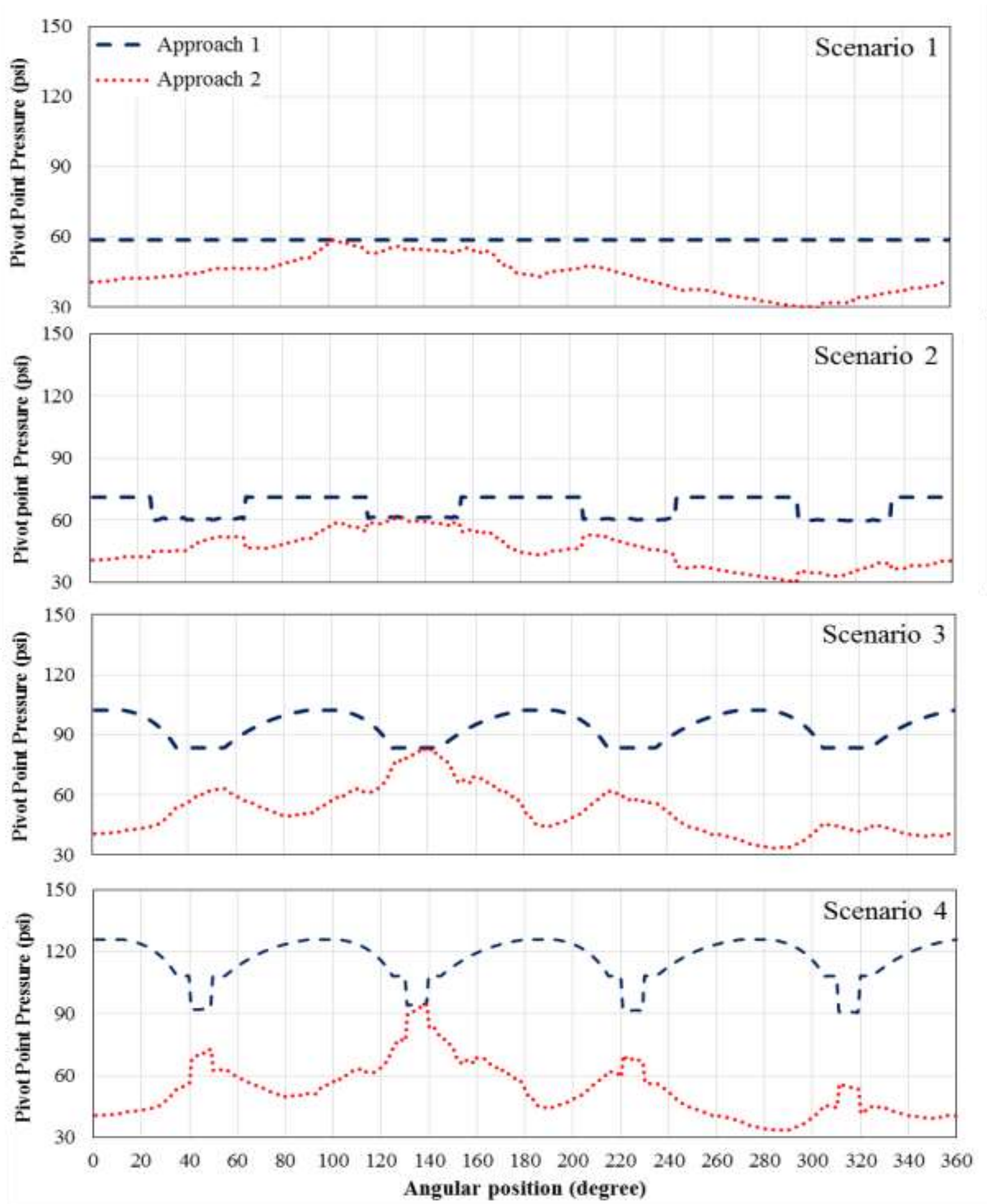

Figure 3. Graphical comparison between Approach 1 where the pressure supplied to the pivot point was held constant and Approach 2 where a VFD was employed to adjust the pump speed to supply the pressure required by all sprinklers on the center pivot. The difference in pivot point pressure at each angular position was used to calculate energy savings achieved by Approach 2. The two curves intersect at the field location of the design pressure.

Table 1. Average elevation difference in the study counties and average energy reduction (%) for 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 equipped with an end gun.
Scenario 3: Standard center pivot system equipped with a corner extension.
Scenario 4: Standard center pivot system equipped with a corner extension and an end gun.

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

The percentage energy reduction by adopting Approach 2 over Approach 1 as a function of the number of center pivot systems is presented in Figure 4. In Scenario 1, the results illustrate that in counties with large in-field differences in elevation such as Cedar, Custer and Antelope, greater percentage of center pivots could reduce energy consumption. In counties with less variable terrain like Butler and Hamilton Counties, more than 50% of the pivots saved no energy.

As we proceed from Scenario 2 to 4, the addition of corner attachments narrowed the range of energy reductions within the county and increased the potential energy savings by nearly 20% (Figure 4). This was because the flow rate changes brought about by the corner attachments became a more significant factor in determining energy savings than changes in field topography. Thus, the major benefit to using a VFD is when the center pivot is equipped with corner attachments like end guns and corner extensions.

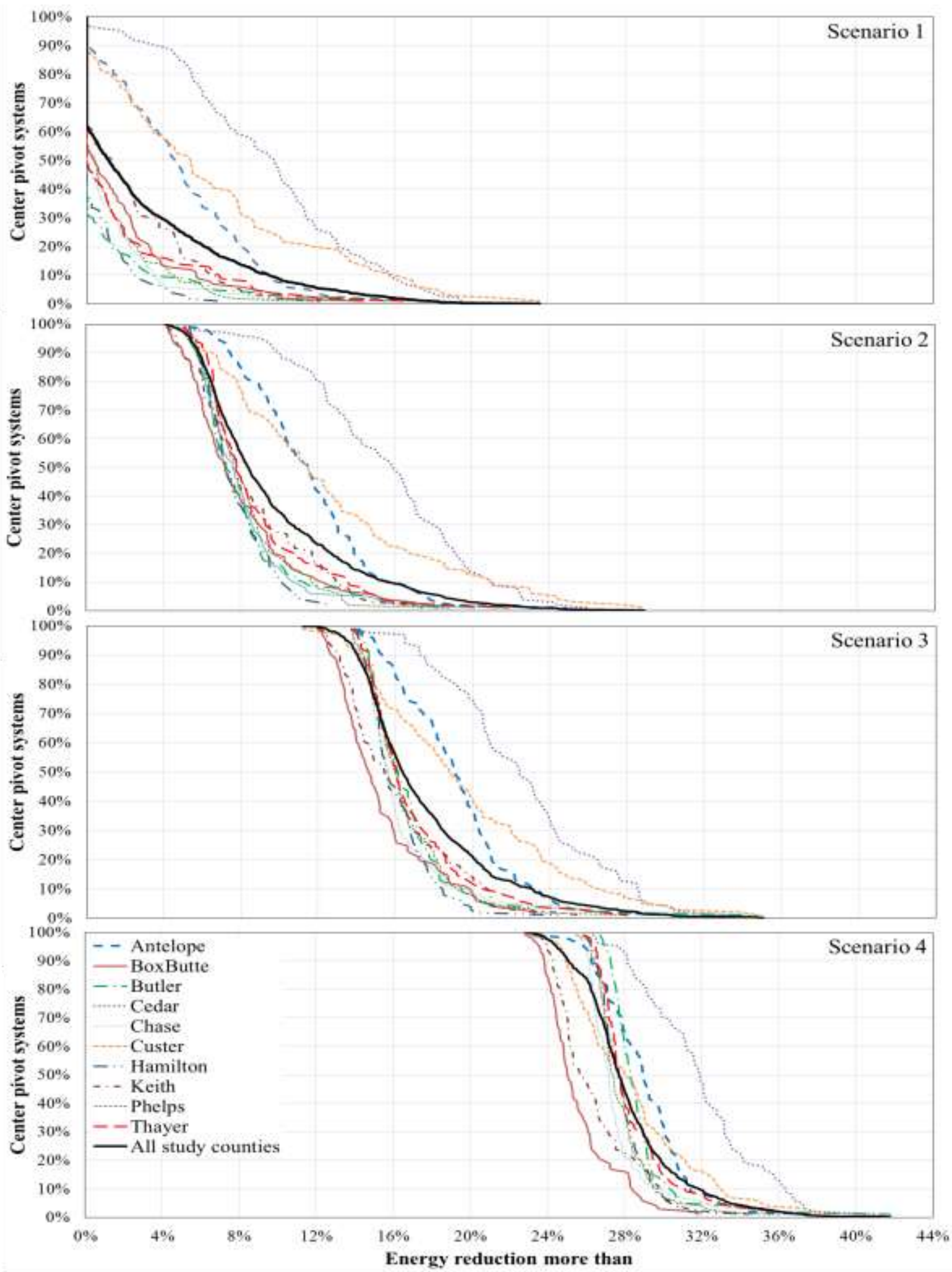

Figure 4. Exceedance functions of energy use reduction by using Approach 2 where a VFD was employed to supply the exact pressure required by all sprinklers on the center pivot compared to Approach 1 for four different pivot installation options.

OPTIMAL LOCATION FOR CONTROL SENSOR PLACEMENT

In advertising, the last tower has been suggested as one place to position a pressure transducer for providing pipeline pressure information to the VFD. Since it is not financially feasible to place a pressure transducer at each pivot tower, the best option is to select the tower that would ensure the minimum required pivot point pressure. We conducted and analysis where the pressure control point was located at each tower. Output from the center pivot hydraulics calculations were used to investigate the tower which would provide the optimal location to place the pressure sensor. At every degree of rotation in 1000 fields, the tower with the lowest pipeline pressure was identified as the optimal location for control sensor placement. These data were pooled to calculate the percentage of angular positions where each of the seven towers was the optimal placement location.

The average percentage of angular positions for placement of a control sensor in each county and the average for 1000 fields are shown in table 2. Based on the analysis, placing a VFD control sensor at the last tower in all cases is ill-advised because the lowest pipeline pressure may occur at other tower locations over 50% of the time. Instead, it is recommended that the pressure control point be determined on a pivot-by-pivot basis by considering field topography and pipeline friction losses.

Table 2. A summary of the average percentage of angular positions where a specific tower was the optimal placement of a VFD control sensor for 1000 center pivot fields located in 10 counties (Brar, 2015).

	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**

SUMMARY

The use of VFD can provide significant savings in terms of energy conservation. However, there are concerns about the cost effectiveness of the approach on a wide scale. The price of VFD is determined by the horsepower requirements of the particular field. Overall, the major factors influencing the energy conservation in this approach were site-specific topographical differences, large changes in flow rate, hours of operation, and shape of pump performance curve. For fields with significant topographic features that include corner attachments, energy cost savings can reach over 30%. Yet despite high potential energy savings, the total capital investment that can be justified for a VFD installation is directly related to the total annual energy cost, the desired return on investment, and the anticipated economic life of the VFD.

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