TECHNICAL NOTES

U.S. DEPARTMENT OF AGRICULTURE NATURAL RESOURCES CONSERVATION SERVICE
ENGINEERING #20 **SPOKANE, WASHINGTON**
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Variable Frequency Drive (VFD) for Irrigation Pumping

(A User's Guide for Conducting Economic Comparisons)

BACKGROUND

An economic evaluation of a pumping plant is necessary to determine if a Variable Frequency Drive, VFD, is cost effective. A comprehensive detailed National technical note is available online which describes the fine points on how VFD's work, specifications and definitions. A link to that note is found in the reference section of this note. An economic comparison spread sheet has been developed by Bonneville Power Administration (BPA) to do complete VFD evaluations and to calculate the cost, savings and payback rate for a planned or existing pump site.

The attached form was developed to assist with the inventory and data collection necessary for conducting evaluations utilizing the BPA evaluation tool. In addition, case studies are provided which are copied from the draft National Technical Note to show how to quickly and easily input data into the economic comparison spread sheet and to explain what it means.

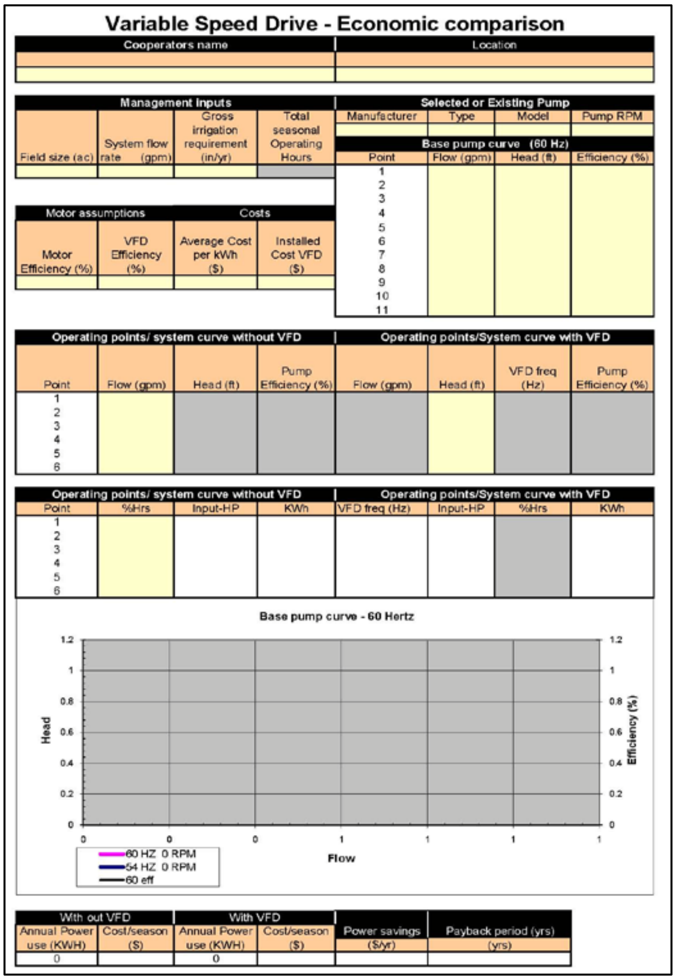
BPA VFD ECONOMIC TOOL (Excel Spreadsheet)

There are four sections to the VFD economic comparison spread sheet. All of the following information and data is required to conduct an evaluation utilizing the BPA economic tool:

1. **System data** – name, location, management inputs, motor data, costs
2. **Pump curve data** –RPM; flow in gpm vs. head in ft, efficiency – enter a minimum of 5 points
3. **Operating points without the VFD** – enter a minimum of 2 points
4. **Operating points with the VFD** - with amount of time (%) for each point.

A pumping plant inventory/data collection form has been prepared (attachment 2) to facilitate the collection of all of the necessary information to run the BPA Evaluation Tool. The BPA Evaluation tool is relatively easy to run as long as all of the required data has been collected. The input sheet for the BPA evaluation tool is shown below for information.

BPA VFD ECONOMIC COMPARISON TOOL INPUT SHEET



Variable Speed Drive - Economic comparison

Cooperators name	Location

Management inputs			
Field size (ac)	System flow rate (gpm)	Gross irrigation requirement (in/yr)	Total seasonal Operating Hours

Selected or Existing Pump			
Manufacturer	Type	Model	Pump RPM

Base pump curve (60 Hz)			
Point	Flow (gpm)	Head (ft)	Efficiency (%)
1			
2			
3			
4			
5			
6			
7			
8			
9			
10			
11			

Motor assumptions		Costs	
Motor Efficiency (%)	VFD Efficiency (%)	Average Cost per kWh ($)	Installed Cost VFD ($)

Operating points/ system curve without VFD				Operating points/System curve with VFD			
Point	Flow (gpm)	Head (ft)	Pump Efficiency (%)	Flow (gpm)	Head (ft)	VFD freq (Hz)	Pump Efficiency (%)
1							
2							
3							
4							
5							
6							

Operating points/ system curve without VFD				Operating points/System curve with VFD			
Point	%Hrs	Input-HP	KWh	VFD freq (Hz)	Input-HP	%Hrs	KWh
1							
2							
3							
4							
5							
6							

With out VFD		With VFD			
Annual Power use (KWH)	Cost/season ($)	Annual Power use (KWH)	Cost/season ($)	Power savings ($/yr)	Payback period (yrs) (yrs)
0		0			

Summary:

The economic comparison spread sheet may be used by others who are designing a VFD. The purpose of this evaluation spread sheet is to determine the value of a VFD and compare with the existing pump or possibly a new pump that fits the site better. **A VFD requires some energy to filter the power and cool the unit, so if there is not enough flow or pressure variation, a VFD could require more energy than the current situation.**

Other benefits and associated values from using a VFD are much harder to determine. The power savings are also very dependent on the type of pump that is being retrofitted or selected. A steeper pump curve would generate more savings. The number of hours the system is operated also directly affects the cost.

The economic comparison spread sheet has comments on certain cells to help explain what to input. The accuracy of the results will only be as good as the accuracy of the input information.

Links:

VFD Economic Comparison spread sheet – **http://www.bpa.gov/Energy/N/agricultural_resources.cfm**
Washington NRCS Construction Specification- **http://www.wa.nrcs.usda.gov/technical/ENG/specifications/**
Fact Sheet and Detailed VFD draft technical note **http://www.wa.nrcs.usda.gov/technical/ENG/index.html**

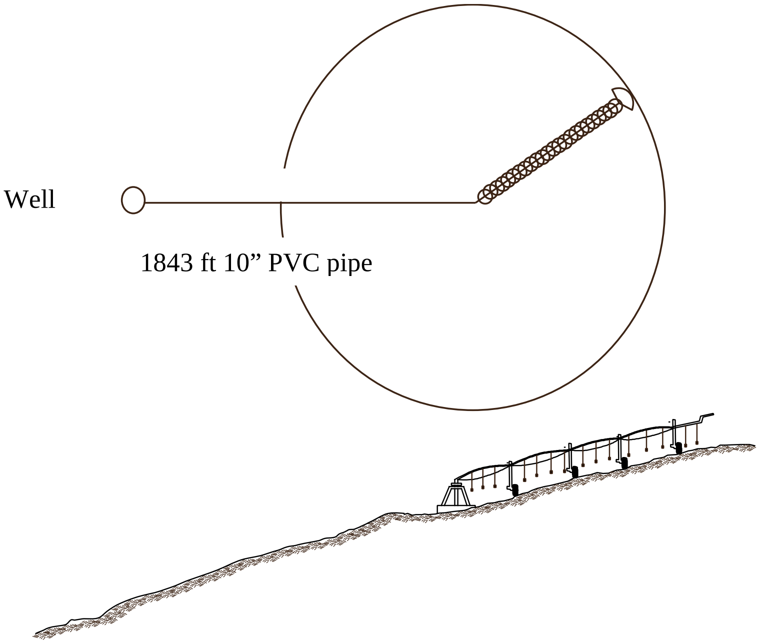
EXAMPLE CASE 1 - Center Pivot Sprinkler on a steeply sloped field

Background

Water is pumped from a well to supply a center-pivot sprinkler system. The pumping plant consists of an electric motor and vertical turbine pump. Power costs are $0.07 per kWh. The sprinkler irrigation system is a MESA (mid-elevation spray application) pivot system with 20-psi pressure regulators and nozzles mounted at 6 feet. The sprinkler uniformity for these types of nozzles is calculated at 85%. The estimated pivot flow rate is 877 gpm (1.95 cfs). The sprinklers irrigate 140 acres of corn with an estimated annual net water requirement of 28 inches (Fig. 1).

The pumping lift is 100 ft. The pivot is irrigating a field that has a fairly uniform slope of 4%. The pump design was based upon delivering the total flow with the pivot oriented uphill on a 4% slope.

Figure 1. Case 1 Farm Layout



Due to the use of pressure regulators in the system, the flow rate is assumed to remain essentially constant for all conditions. However, it is necessary to determine the total dynamic head (TDH) for the pivot at different positions.

Because of the field slope, the pressure at the distal end of the pivot lateral is constantly changing. The pressure regulators provide uniform pressure and uniformity to the nozzles but the energy use changes when adjusting the pressure to match the conditions required on the field. This analysis can range from simple to complicated. In most cases a simplified analysis will provide good information on energy and cost savings. To make evaluation easier, the field is divided into three major control sections:

1) pivot operating uphill
2) pivot operating on the level
3) pivot operating downhill

The head requirements for the three selected conditions are summarized below, in Table 1.

Table 1 – Total Dynamic Head, TDH requirements

Condition	**TDH Uphill Condition**	**TDH Level Condition**	**TDH Downhill Condition**
% of time in condition	**25%**	**50%**	**25%**
Pivot point pressure	40 psi	40 psi	25 psi*
Elevation gain	+22.9 psi	0 psi	0 psi
Friction loss in mainline	3.16 psi	3.16 psi	3.16 psi
Miscellaneous losses	3 psi	3 psi	3 psi
Pump losses	1.5 psi	1.5 psi	1.5 psi
Pump column lift	43.3 psi	43.3 psi	43.3 psi
TDH	**113.7 psi = 262.6 ft**	**90.8 psi = 209.8 ft**	**78 psi = 175.5 ft**

* When the pivot is in the downhill condition the minimum pressure of 20 psi plus 5 psi for the pressure regulators still needs to be supplied. The slope which is steeper than the friction slope will provide the rest of the necessary pressure.

System Data

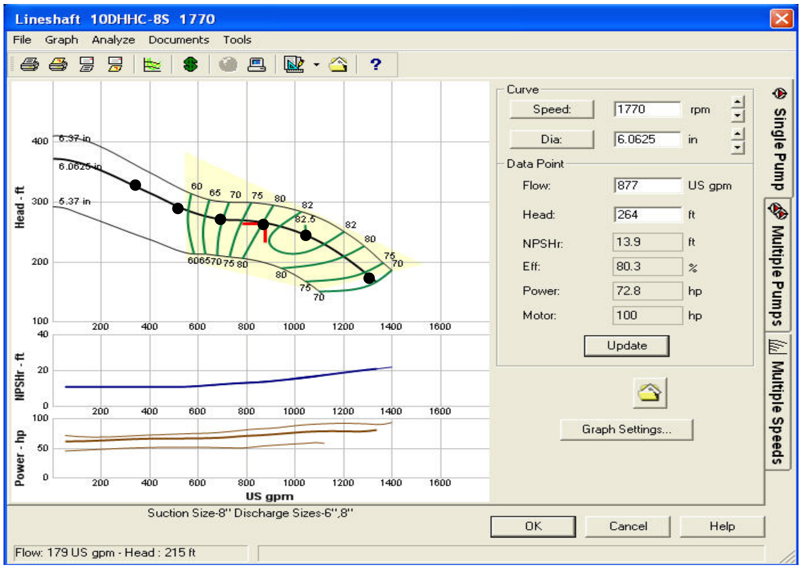
The pivot applies 877 gal/min of water on 140 acres. The total operating hours needs to be either calculated or entered. The operating hours can be entered directly into cell E11 or, if the net irrigation and sprinkler uniformity are known, the hours can be calculated. For this example, the sprinkler uniformity efficiency is 85% with a net application of 28"/ year, the gross application would be 28"/0.85 = 32.9" in cell D11.

For the existing condition the pump provides 877 gpm and a TDH of 263 ft. all the time.

Pump Curve Data

Select a Gould 10DHHC with 8 stages operating at 1770 RPM. The pump curve is shown in Figure 2. The points used in the case study are shown in Table 2.

Figure 2. Gould Pump Curve



Curve
Speed: 1770 rpm
Dia: 6.0625 in
Data Point
Flow: 877 US gpm
Head: 264 ft
NPSHr: 13.9 ft
Eff: 80.3 %
Power: 72.8 hp
Motor: 100 hp

Suction Size-8" Discharge Sizes-6",8"

Flow: 179 US gpm - Head : 215 ft

Table 2 - Points from manufacturers pump curve

Q (gpm)	Head (ft)	Efficiency (%)
352	322	42
528	290	58
704	270	70
880	264	80
1056	241	82
1325	168	70

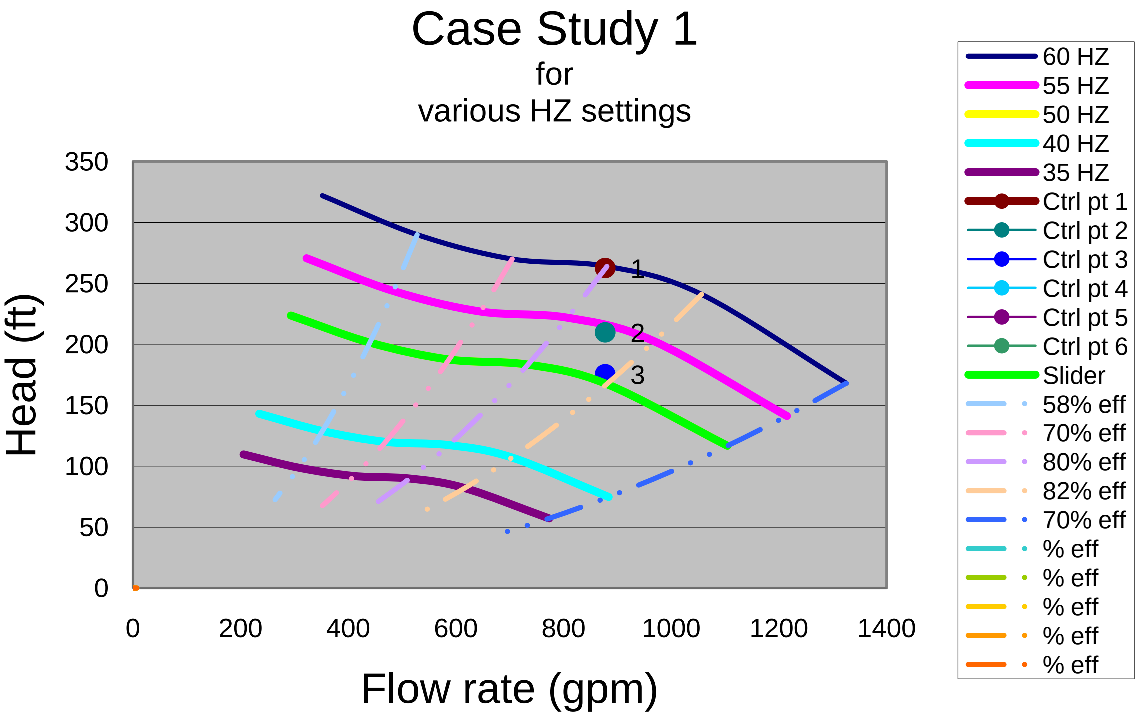
Operating points without a VFD

The flow is the same for this pivot under all conditions. Without a VFD, excess pressure is dissipated through the pressure regulators along the pivot. When the pivot is operating on both level and downhill positions, the pressure will increase in the system, only to be reduced through the pressure regulators. The estimated power cost is $9,651 per season.

Operating points with a VFD

Again the flow will remain the same for the pivot in all positions. The pivot will operate approximately 25% of the time in the uphill condition, 50% of the time in the level condition and 25% of the time downhill condition. The VFD will adjust the speed of the motor to keep the pressure constant at the pivot point.

Figure 3. Pump Curve with VFD



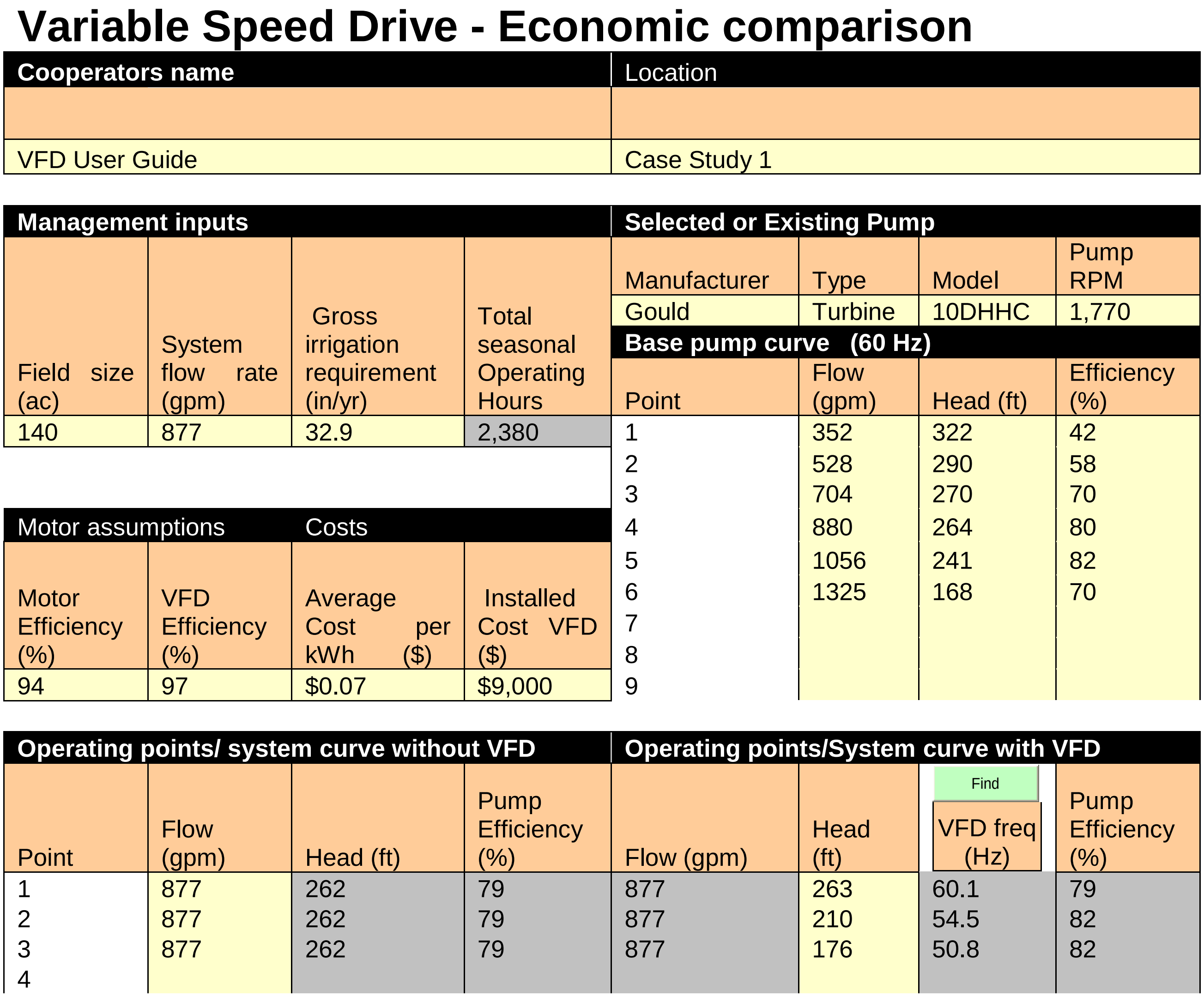
The plot of the new pump curve with the VFD is shown in Figure 3. The plot shows operating points, the system curve and the approximated efficiency curves. The 3 points shown are the operating points entered in the case study. The new efficiencies at the various TDH values are:

Point 1 - TDH = 262 ft – efficiency = 79%
Point 2 - TDH = 210 ft – efficiency = 81%
Point 3 - TDH = 175 ft – efficiency = 82%

The VFD adds another loss in the form of efficiency. The default value for the VFD efficiency is approximately 97%. The power requirements for the various operating points are 80 hp, 62 hp, and 52 hp, respectively.

The actual energy cost with the VFD for this case study is estimated at $7,986 per season. The savings in energy operating under these conditions would be $1,665 per season. The complete input and output data from the economic comparison spread sheet is shown below. With the initial cost at $9,000, the payback period on the VFD would be 5.4 years.

Figure 4. Case Study 1 - Economic Comparison



Variable Speed Drive - Economic comparison

Cooperators name	Location
VFD User Guide	Case Study 1

Management inputs

Field size (ac)	System flow rate (gpm)	Gross irrigation requirement (in/yr)	Total seasonal Operating Hours
140	877	32.9	2,380

Selected or Existing Pump

Manufacturer	Type	Model	Pump RPM
Gould	Turbine	10DHHC	1,770

Base pump curve (60 Hz)

Point	Flow (gpm)	Head (ft)	Efficiency (%)
1	352	322	42
2	528	290	58
3	704	270	70
4	880	264	80
5	1056	241	82
6	1325	168	70
7			
8			
9			

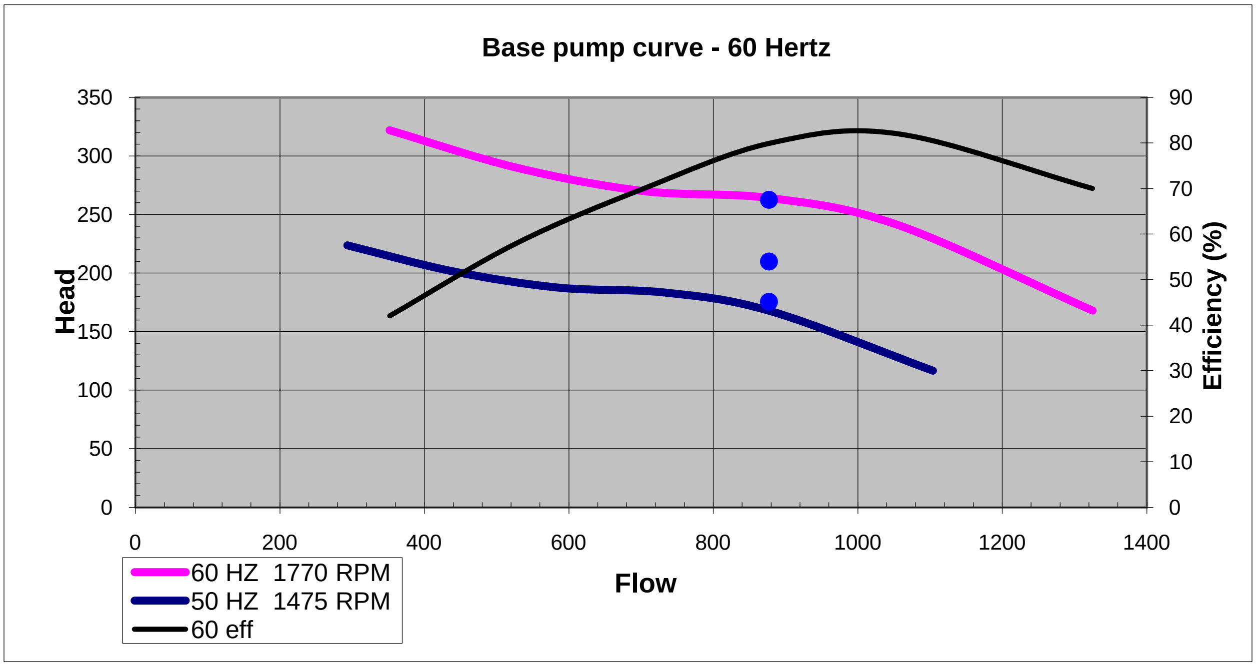
Motor assumptions		Costs	
Motor Efficiency (%)	VFD Efficiency (%)	Average Cost per kWh ($)	Installed Cost VFD ($)
94	97	$0.07	$9,000

Operating points/ system curve without VFD				**Operating points/System curve with VFD**			
Point	Flow (gpm)	Head (ft)	Pump Efficiency (%)	Flow (gpm)	Head (ft)	Find VFD freq (Hz)	Pump Efficiency (%)
1	877	262	79	877	263	60.1	79
2	877	262	79	877	210	54.5	82
3	877	262	79	877	176	50.8	82
4							

Figure 5. VFD Economic Comparison, cont.

Operating points/ system curve without VFD				**Operating points/System curve with VFD**			
Point	%Hrs	Input-HP	KWh	VFD freq (Hz)	Input-HP	%Hrs	KWh
1	25%	78	34,463	60.1	80	25%	35681
2	50%	78	68,943	54.5	62	50%	55394
3	25%	78	34,471	50.8	52	25%	23012
4							

Without VFD		With VFD		Power savings	Payback period (yrs)
Annual Power use (KWH)	Cost/season ($)	Annual Power use (KWH)	Cost/season ($)	($/yr)	(yrs)
137,877	$9,651.41	114087	$7,986.12	$1,665.28	5.4



EXAMPLE CASE 2 - Center pivot sprinkler with a declining water table.

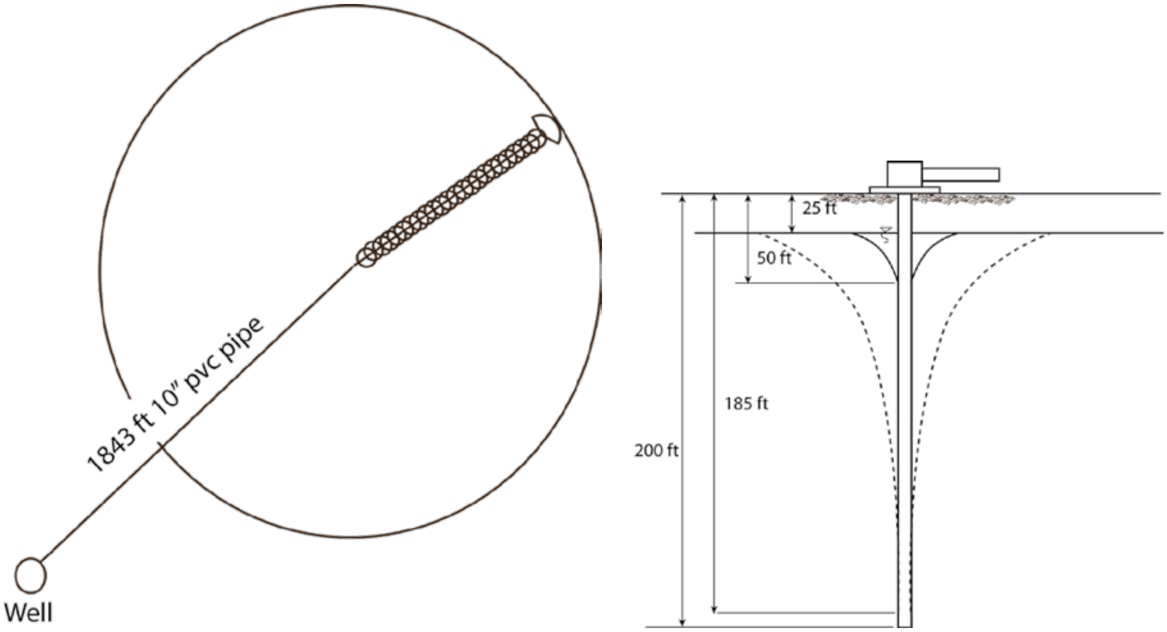
Background

Water is supplied to a Pivot from a single well located in the Odessa Aquifer. The pumping lift from the well ranges from 50 ft at the beginning of the irrigation season to 185 ft at the end of the season. The sprinkler system operates close to its design point at the end of the season, but the producer must be careful to avoid air entrainment due to inadequate water depth over the pump inlet.

System Data

The sprinkler irrigation system is a Low Elevation Spray Application (LESA) pivot system on relatively level ground with the pivot point located 5 ft higher than the well. It is nozzled for 750 gpm (1.67 cfs) at 36 psi (ground level at Pivot) and the sprinkler package uniformity is 90%. Pressure regulators set at 15 psi are used on the system to control the flow rate during the season. The sprinkler height is 4 ft above ground. The pivot irrigates 122 acres of corn with a net irrigation requirement of 24 inches annually and the power costs are $0.07 per Kw-hr (Fig 6).

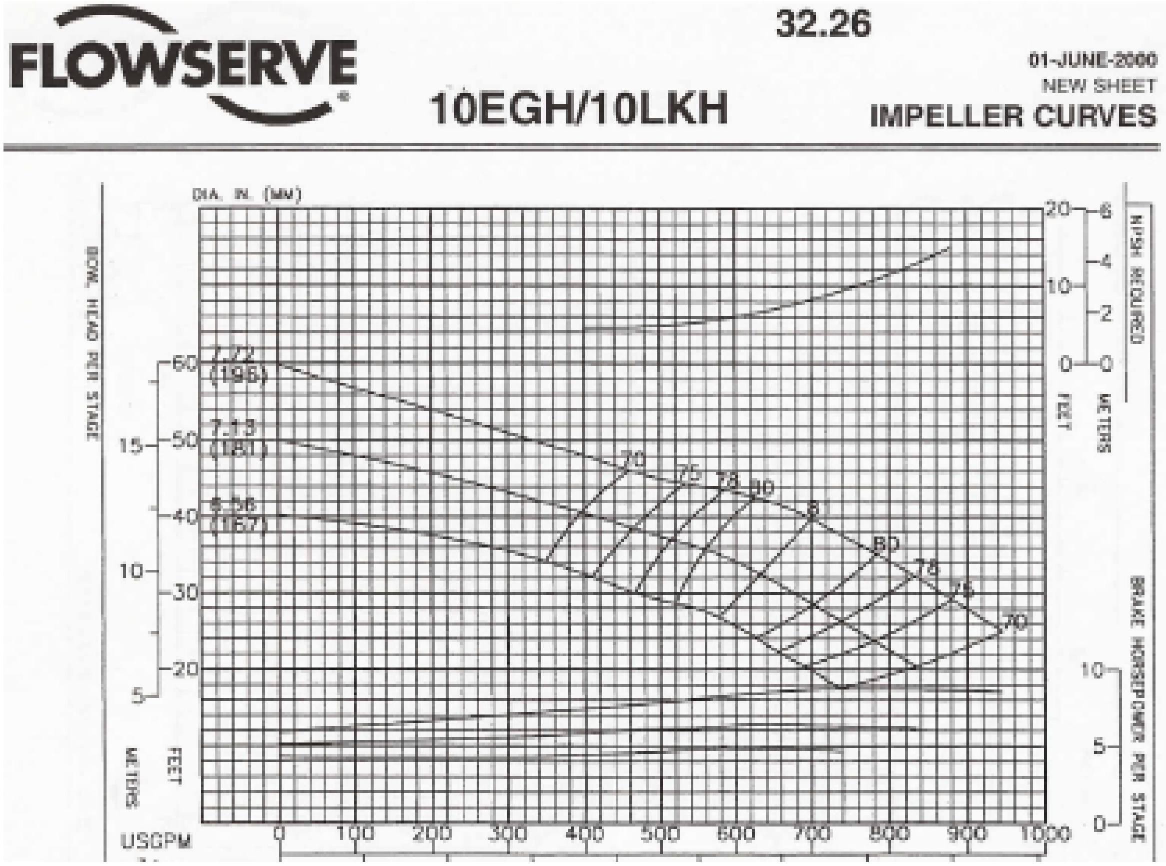
Figure 6. Case Study 2, Farm Layout



Pump Curve Data

The pumping plant is an electric motor connected to a vertical turbine pump, a Flowserve 10EGH operating at 1770 rpm. The pump curve is found on Figure 7. The pump has 8 stages of 7.72 inch diameter impellers. Each stage boosts the pressure and maintains the flow. This data from the pump curve is entered into the economic comparison spread sheet below. The complete pump curve data is shown in Attachment 1.

Figure 7. Case Study 2 - Pump Curve



The TDH at the beginning and end of the season are summarized below.

Table 3 – Case Study 2 - TDH results

	Season Start TDH	End of Season TDH
Static Lift	25 ft	25 ft
Drawdown	25 ft	160 ft
Pivot Pressure	83.2 ft	83.2 ft
Column and Discharge Friction losses	4.8 ft	4.8 ft
Elevation from well to pivot	5.0 ft	5.0 ft
Mainline Friction losses	17.7 ft	17.7 ft
Total	160.7 use 161	295.7 use 296

The pivot applies 26.7 gross inches of water to the field. (Net irrigation of 24”/90% uniformity) The estimated seasonal hours of operation is 1963 hrs (T=DA/Q; 26.7inches x 122acres/1.67cfs).

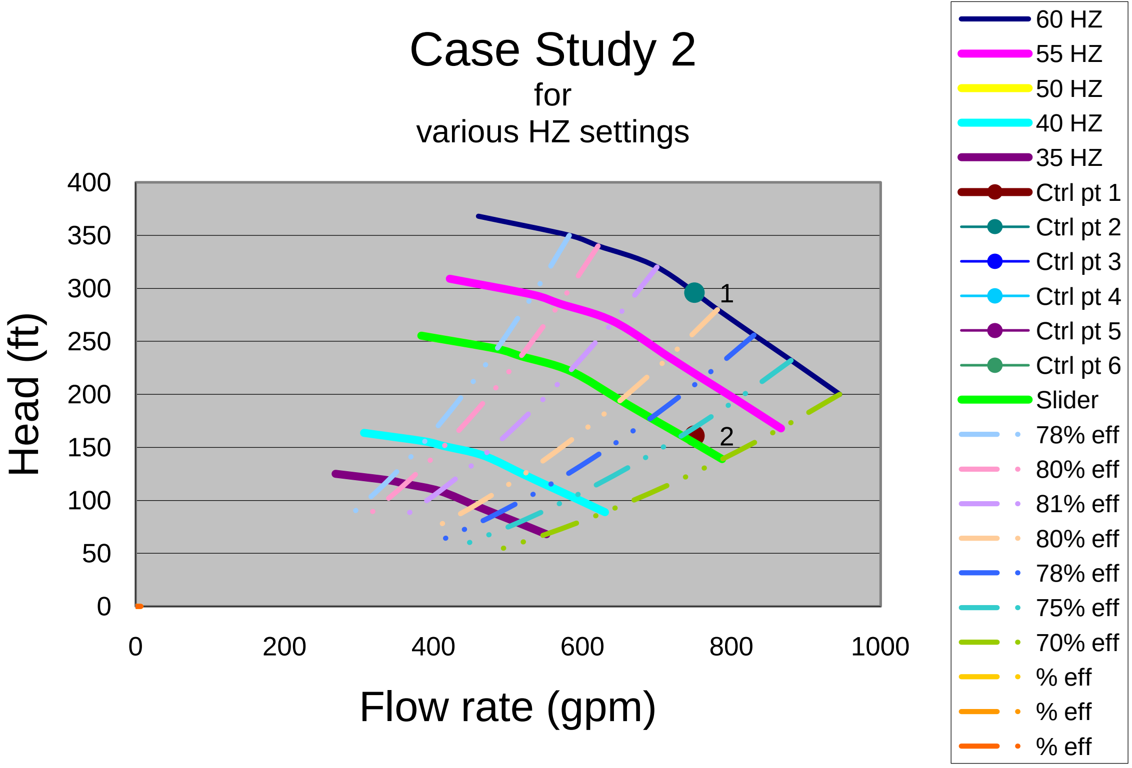
Operating points without VFD

The maximum required TDH is 296 ft. Without a VFD the system would operate at this head all season. Early in the season when the water is higher in the well the excess pressure would be dissipated through valves or the pressure regulators. Annual operating cost without the VFD is estimated at $7,573 for the season. .

Operating points with VFD

With the VFD, the pressure would remain constant at the pivot throughout the entire season. A pressure transducer would monitor and maintain a set pressure point. The new pump curve is shown in Figure 8.

Figure 8. Case Study 2 - New pump curve



Enter all the data into the economic comparison spread sheet to evaluate the 2 conditions.

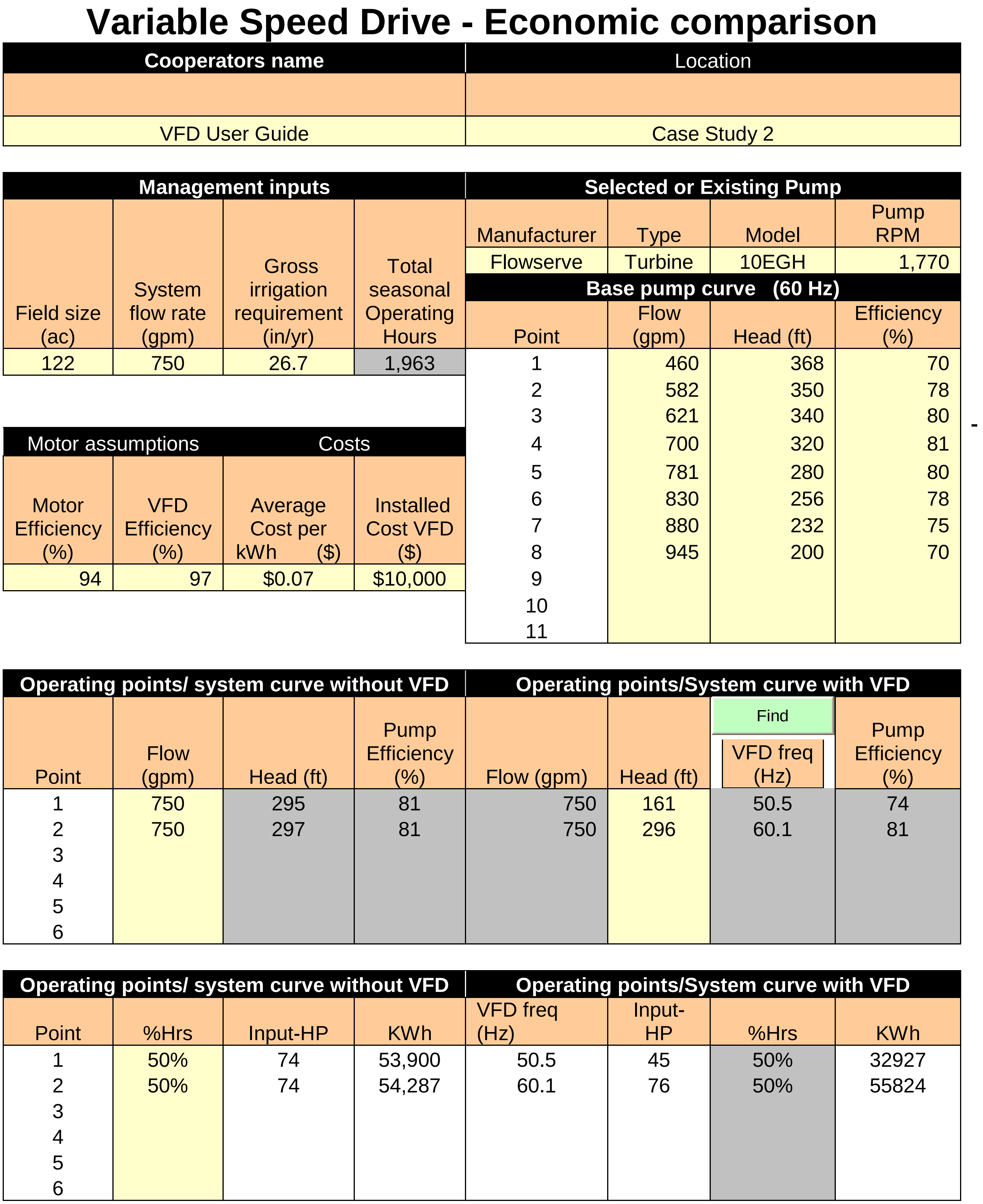
Condition 1 - TDH = 296 ft – efficiency = 80.5%
Condition 2 - TDH = 161 ft – efficiency = 75%

The VFD adds another loss in the form of efficiency. The default value for VFD's is approximately 97%. Horsepower and energy input for the two conditions are 76 hp and 45 hp, respectively.

The actual energy cost is based upon the percent of the total hours that the system is operated. Assuming the time is split between the 2 operating conditions the energy savings would be $1,361 per season.

The annual or seasonal savings is compared to the cost of the VFD to calculate the payback period would be 7.4 years. The second case study economic comparison input and output is shown below.

Figure 9. Case Study 2 - Economic Comparison



Variable Speed Drive - Economic comparison

Cooperators name	Location
VFD User Guide	Case Study 2

Management inputs

Field size (ac)	System flow rate (gpm)	Gross irrigation requirement (in/yr)	Total seasonal Operating Hours
122	750	26.7	1,963

Selected or Existing Pump

Manufacturer	Type	Model	Pump RPM
Flowserve	Turbine	10EGH	1,770

Base pump curve (60 Hz)

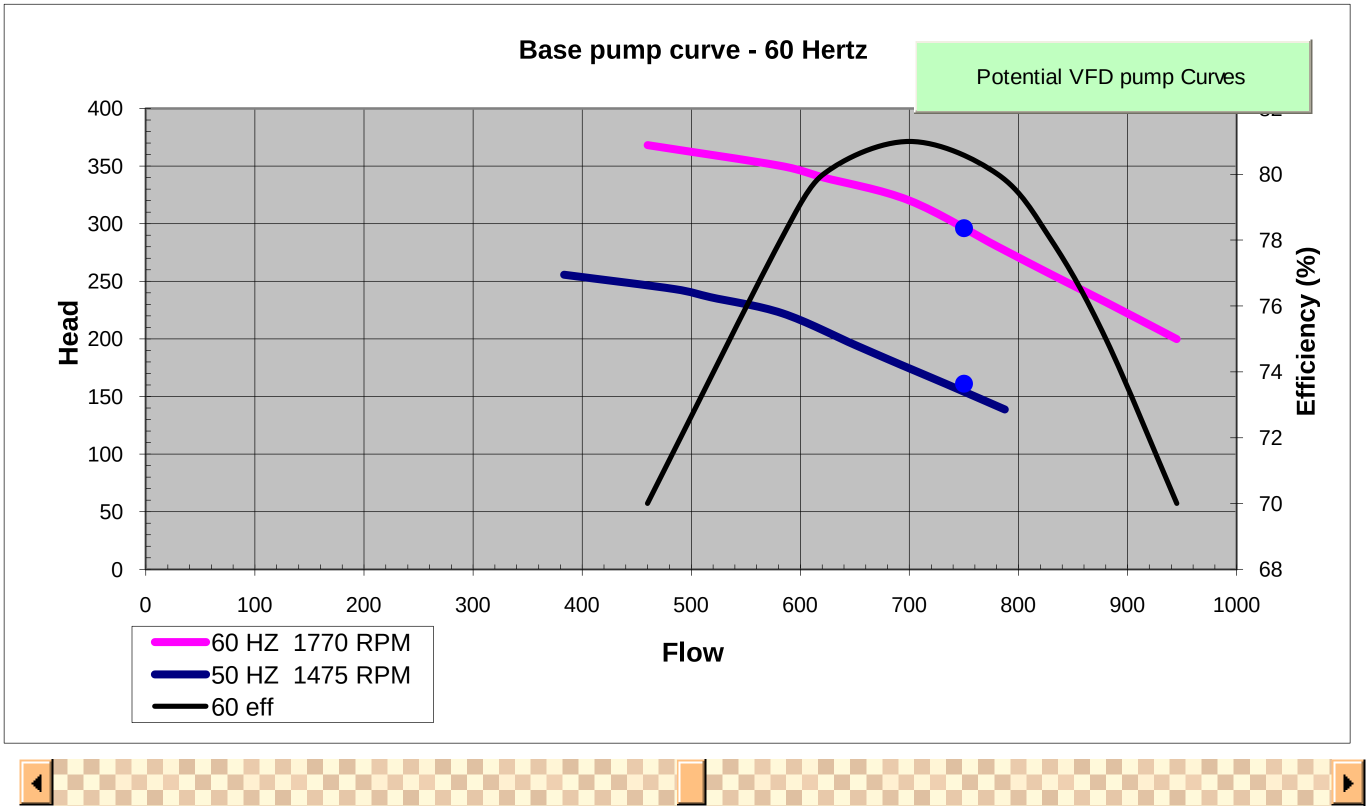
Point	Flow (gpm)	Head (ft)	Efficiency (%)
1	460	368	70
2	582	350	78
3	621	340	80
4	700	320	81
5	781	280	80
6	830	256	78
7	880	232	75
8	945	200	70
9			
10			
11			

Motor assumptions		Costs	
Motor Efficiency (%)	VFD Efficiency (%)	Average Cost per kWh ($)	Installed Cost VFD ($)
94	97	$0.07	$10,000

Operating points/ system curve without VFD				Operating points/System curve with VFD			
Point	Flow (gpm)	Head (ft)	Pump Efficiency (%)	Flow (gpm)	Head (ft)	Find VFD freq (Hz)	Pump Efficiency (%)
1	750	295	81	750	161	50.5	74
2	750	297	81	750	296	60.1	81
3							
4							
5							
6							

Operating points/ system curve without VFD				Operating points/System curve with VFD			
Point	%Hrs	Input-HP	KWh	VFD freq (Hz)	Input-HP	%Hrs	KWh
1	50%	74	53,900	50.5	45	50%	32927
2	50%	74	54,287	60.1	76	50%	55824
3							
4							
5							
6							

Figure 10. Case Study 2 - VFD Pump curve and Economic Analysis



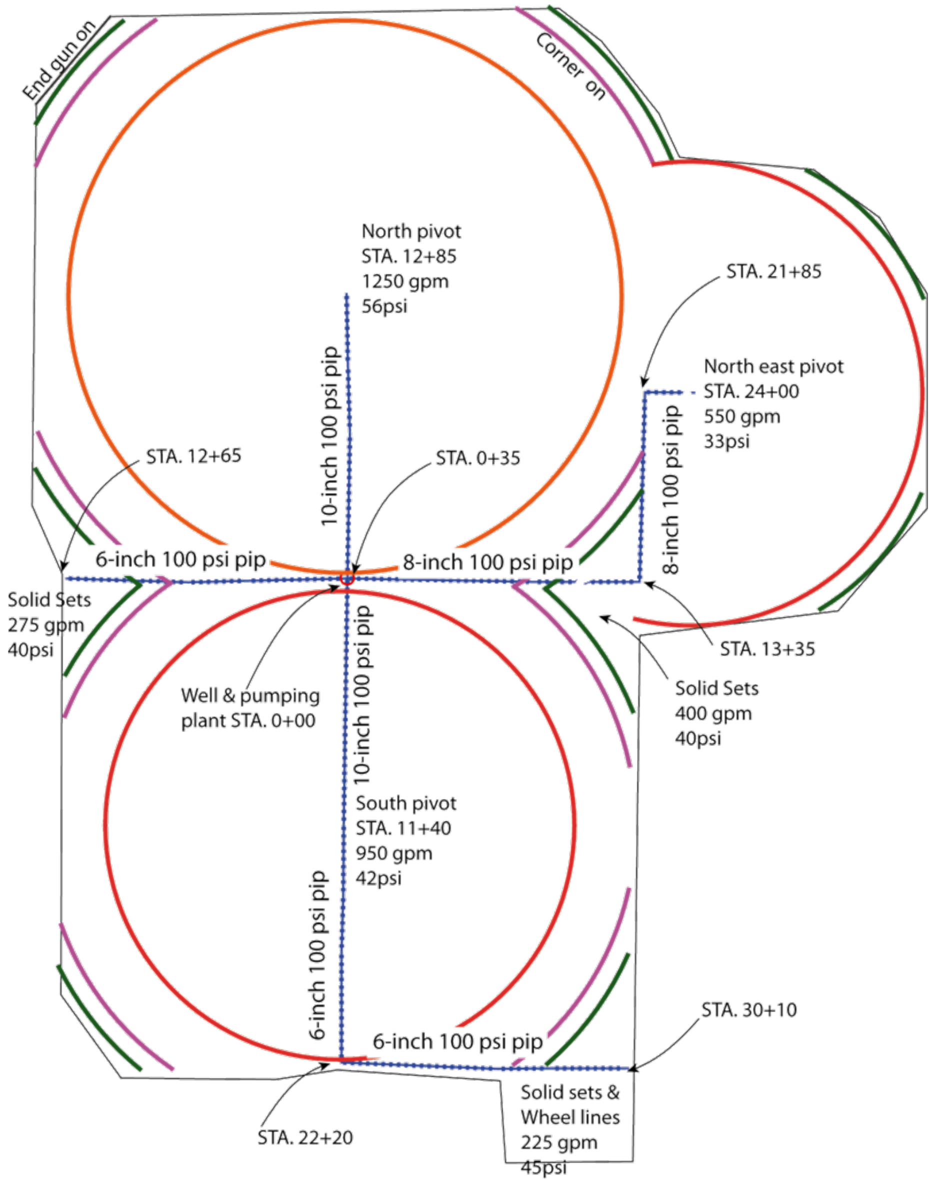
Without VFD		With VFD		Power savings	Payback period (yrs)
Annual Power use (KWH)	Cost/season ($)	Annual Power use (KWH)	Cost/season ($)	($/yr)	(yrs)
108,187	$7,573.08	88751	$6,212.56	$1,360.52	7.4

EXAMPLE CASE 3 - Multiple fields served by one pump

Background

This farm has 360 acres irrigated by three pivots, wheel lines and solid set sprinklers (Fig. 10). Two of the pivots have corner systems. All of the pivots have end guns. The pipe sizes and pressure requirement are also shown on fig 11. The fields are all the same elevation and are planted in a variety of crops: potatoes, alfalfa, small grains, sugar beets, and corn. The water source for the fields is a single well. The power source is electricity at $0.10 per kilowatt-hr. The average pumping season is 1700 hours. The pump is an older vertical turbine operating at 1770 rpm, with 3 stages, each 10.3 inch diameter. The operator would like to install a VFD to facilitate management, to save energy and to reduce costs.

Figure 11. Case Study 3, Farm Layout



System Data

The operating scenarios evaluated are as follows:

(1) All 3 pivots with both corner arms fully extended with all 3 end guns operating
(2) All 3 pivots with both corner arms mostly extended with 1 or 2 end guns operating
(3) All 3 pivots with both corner arms fully retracted with all 3 end guns off
(4) North pivot corner arm mostly extended with end gun off and solid sets operating; or south pivot corner arm fully extended with end gun operating and solid sets operating
(5) Northeast pivot with end gun operating: or south pivot corner arm mostly retracted with end gun off

There are other scenarios possible. These were chosen as the most common and the percent of time for each is 5%, 25%, 50%, 15%, and 5%, respectively. The motor efficiency is 95%. The VFD is 97% efficient.

Pump Curve Data

The pump curve information is taken from the manufacturer's chart and shown in Table 4.

Table 4 - Existing pump curve for Case 3

Pump curve for existing Johnson pump, 14ECII		
Q (gpm)	Pump TDH (ft)	Pump Efficiency %
560	286	29
700	278	35
1000	270	49
1200	264	56
1400	252	63
1770	228	73
2100	219	79
2350	216	82.5
2750	190	81.3

Operating points without VFD

Table 5 shows the pressure requirements for the different conditions using operating pressures and friction loss equations. The pressure requirements are summarized in Table 6. Any excess head is burned off through pressure regulators and valves.

Table 5 - Head and flow summary without VFD

System operation table, no VFD						
Scenario	Q (gpm)	Pump TDH (ft)	Efficiency (%)	Input HP (hp)	Long-term Operation (%)	Power costs @ $0.10/kw-hr
1	2750	192	81.5	172	5	$1094
2	2350	213	81.8	162	25	$5150
3	1770	232	73.3	149	50	$9444
4	1200	261	56.1	148	15	$2818
5	560	283	28.9	146	5	$926

The estimated seasonal operating cost without the VFD is $19,432.

Operating points with VFD

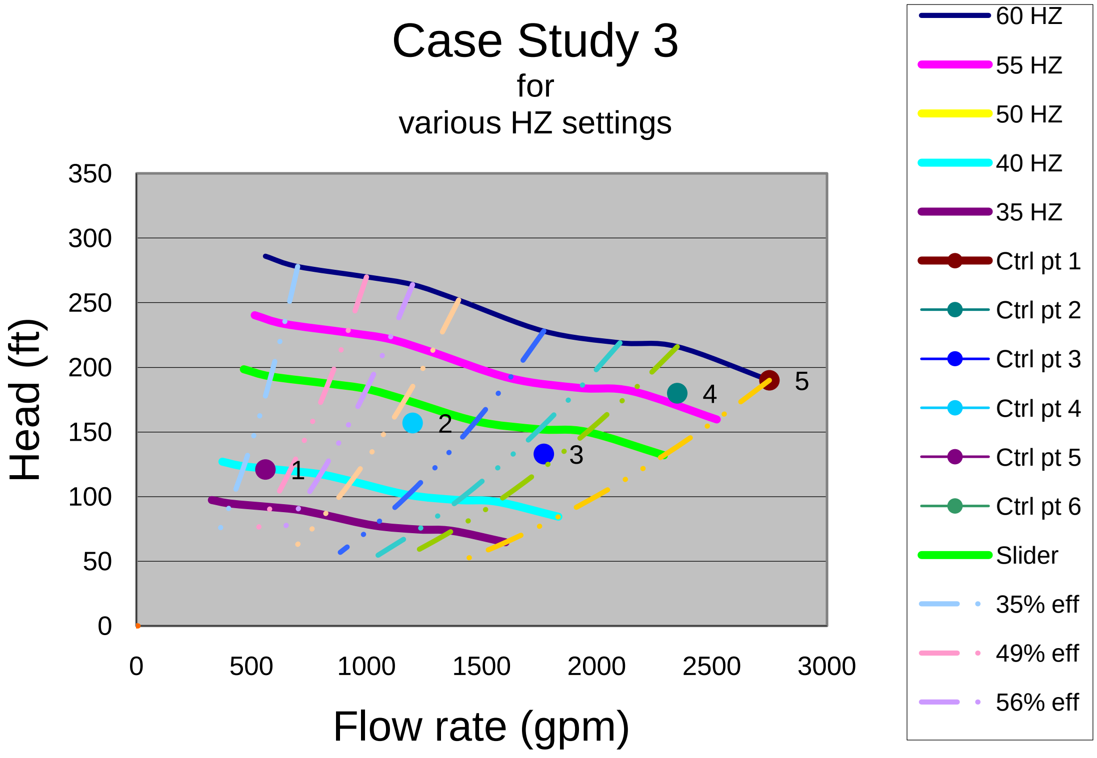
There are two control scenarios for VFD. One would maintain a constant pressure and vary the flow rate while the other would vary both flow rate and head. For this example a VFD that can vary both flow rate and head is selected. Determine the flow and head requirements for each control point. The economic comparison spread sheet is used to estimate the new efficiencies and calculate the power requirements and calculate the cost for each scenario. The inputs are summarized in Table 6. The “Input HP” column includes both the motor and VFD efficiencies.

Table 6 – Head and flow summary with VFD

System operation table, with VFD						
Scenario	Q (gpm)	Pump TDH (ft)	Efficiency (%)	Input HP (hp)	Long-term Operation (%)	Power costs @ $0.10/kw-hr
1	2750	190	81	176	5	$1116
2	2350	180	82	141	25	$4464
3	1770	133	81	80	50	$5050
4	1200	157	66	78	15	$1483
5	560	121	42	44	5	$281

The total estimated annual power cost with the VFD is $12,394 with a resulting estimated savings of $7,038 per season.

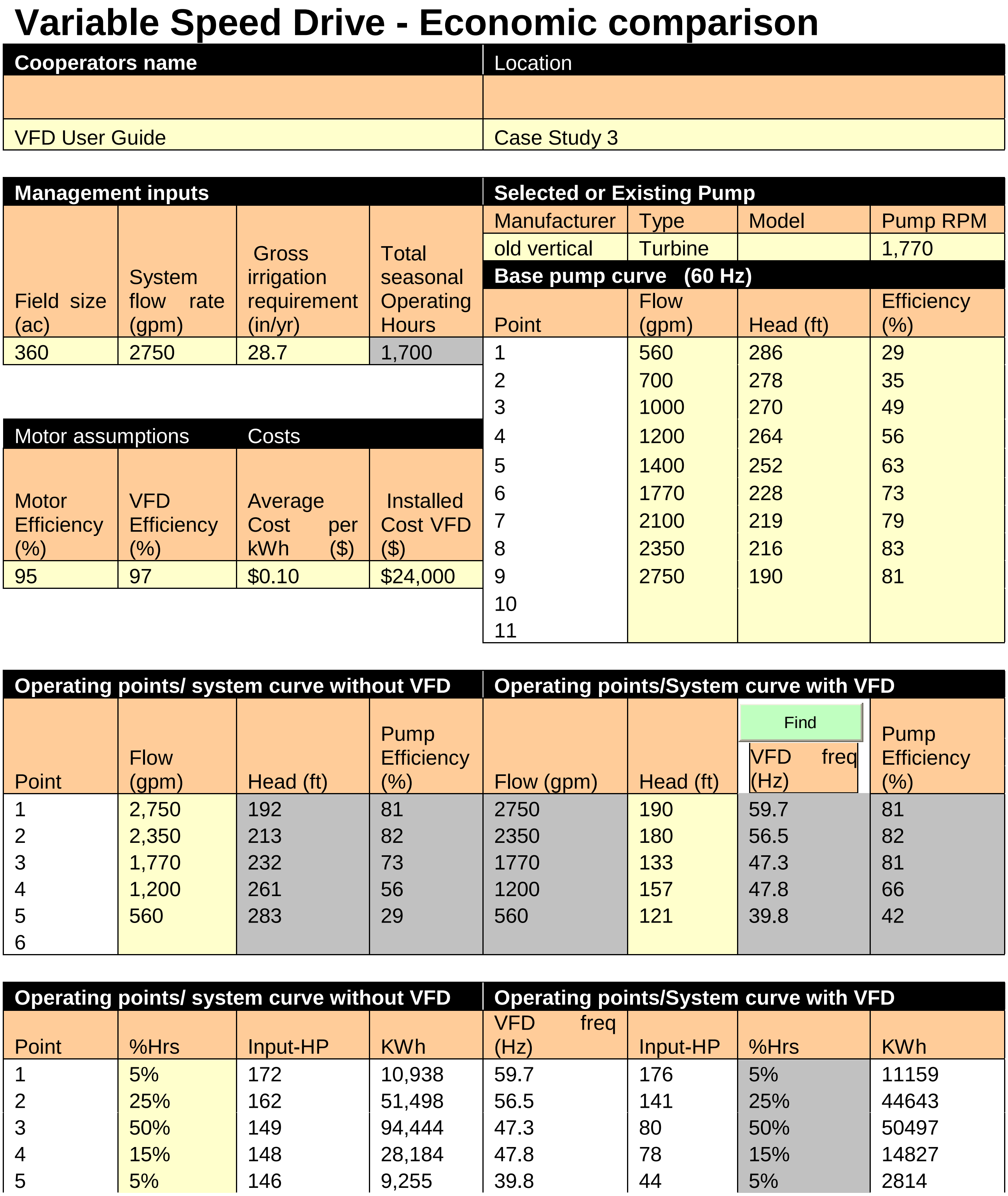
Figure 12. Case Study 3 - Pump Curve



This information can be used to calculate the payback period which is 3.7 years. Several other factors need to be considered in the payback calculations including the escalating cost of energy and system management. Being able to manage the system has always proven to save both water and energy, which saves money.

A summary of the economic comparison of the inputs and outputs for Case 3 is shown below.

Figure 13. Case Study 3 - Economic Comparison



Variable Speed Drive - Economic comparison

Cooperators name	Location
VFD User Guide	Case Study 3

Management inputs

Field size (ac)	System flow rate (gpm)	Gross irrigation requirement (in/yr)	Total seasonal Operating Hours
360	2750	28.7	1,700

Selected or Existing Pump

Manufacturer	Type	Model	Pump RPM
old vertical	Turbine		1,770

Base pump curve (60 Hz)

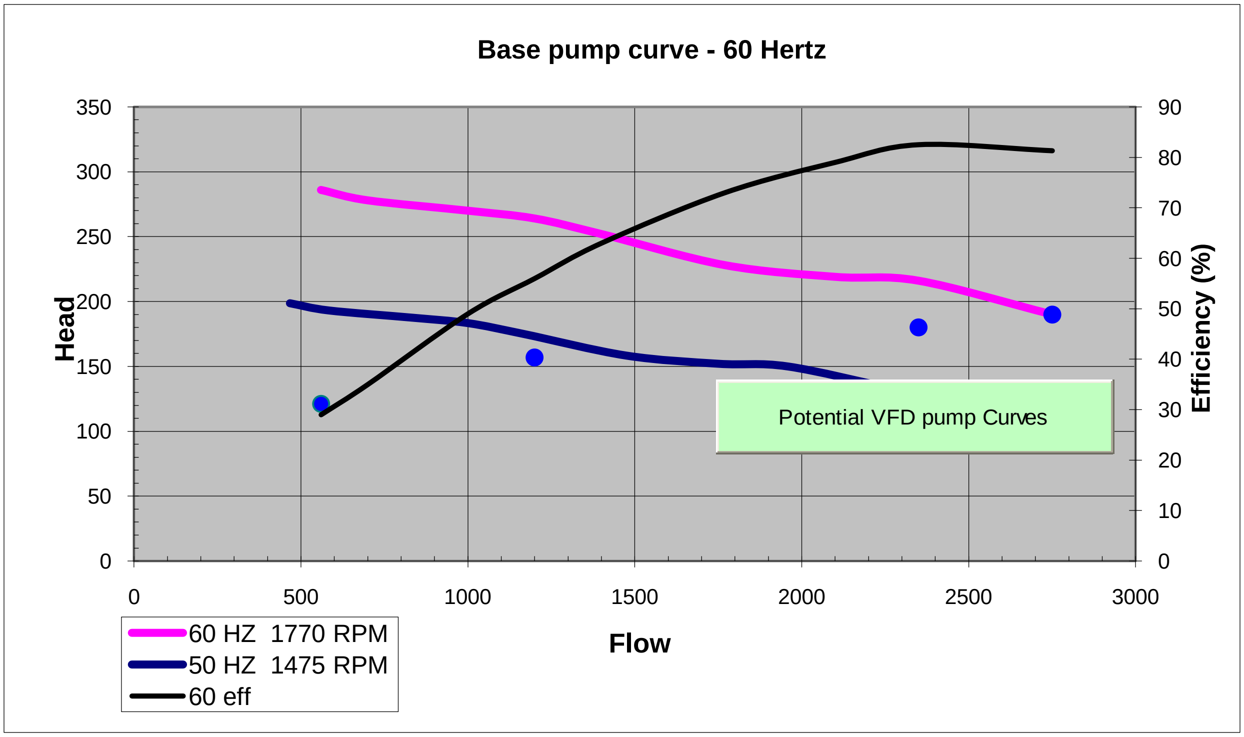
Point	Flow (gpm)	Head (ft)	Efficiency (%)
1	560	286	29
2	700	278	35
3	1000	270	49
4	1200	264	56
5	1400	252	63
6	1770	228	73
7	2100	219	79
8	2350	216	83
9	2750	190	81
10			
11			

Motor assumptions		Costs	
Motor Efficiency (%)	VFD Efficiency (%)	Average Cost per kWh ($)	Installed Cost VFD ($)
95	97	$0.10	$24,000

Operating points/ system curve without VFD				**Operating points/System curve with VFD**			
Point	Flow (gpm)	Head (ft)	Pump Efficiency (%)	Flow (gpm)	Head (ft)	Find VFD freq (Hz)	Pump Efficiency (%)
1	2,750	192	81	2750	190	59.7	81
2	2,350	213	82	2350	180	56.5	82
3	1,770	232	73	1770	133	47.3	81
4	1,200	261	56	1200	157	47.8	66
5	560	283	29	560	121	39.8	42
6							

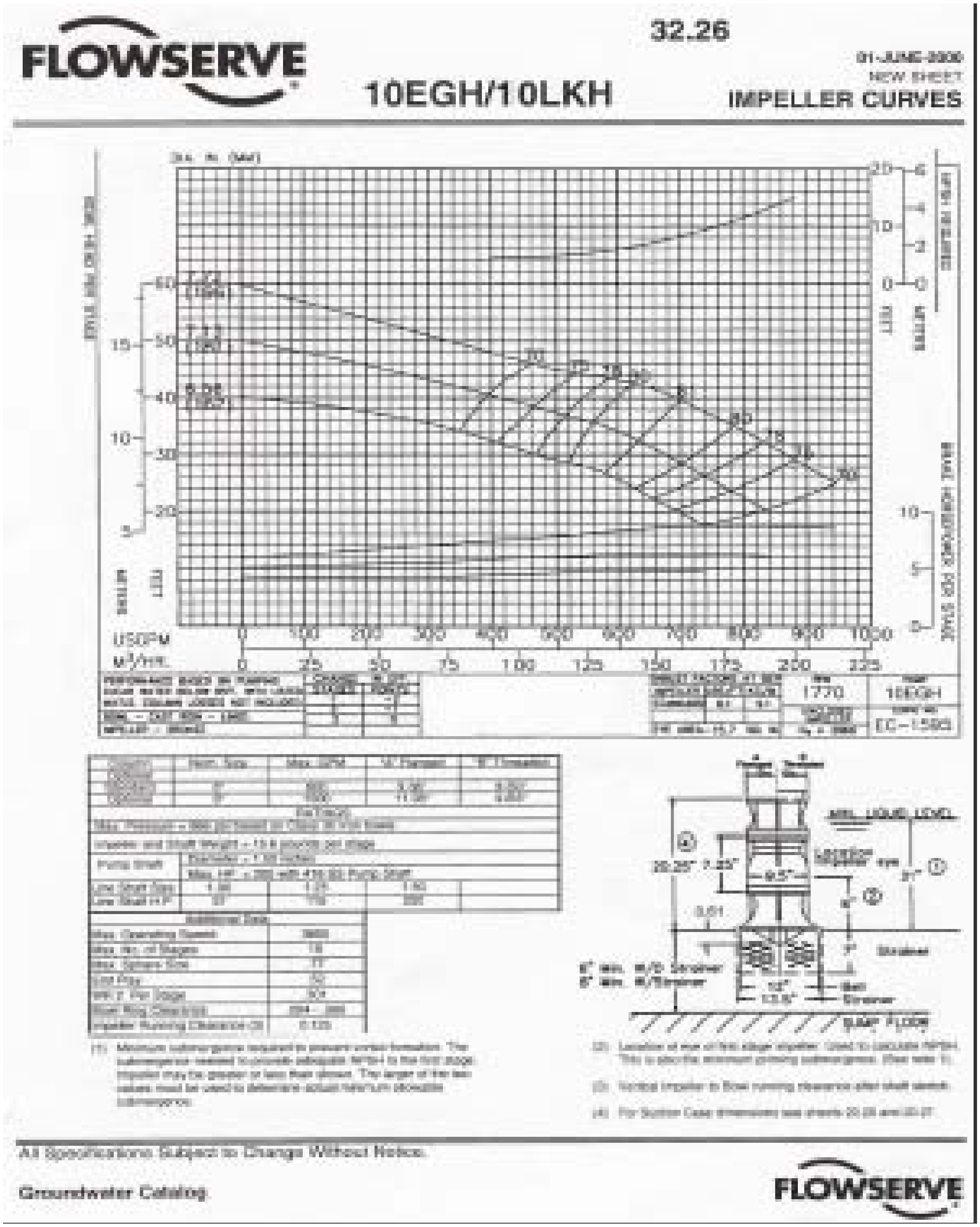
Operating points/ system curve without VFD				**Operating points/System curve with VFD**			
Point	%Hrs	Input-HP	KWh	VFD freq (Hz)	Input-HP	%Hrs	KWh
1	5%	172	10,938	59.7	176	5%	11159
2	25%	162	51,498	56.5	141	25%	44643
3	50%	149	94,444	47.3	80	50%	50497
4	15%	148	28,184	47.8	78	15%	14827
5	5%	146	9,255	39.8	44	5%	2814

Figure 14. Case Study 3 – VFD Pump curve and Economic Analysis



Without VFD		With VFD		Power savings	Payback period (yrs)
Annual Power use (KWH)	Cost/season ($)	Annual Power use (KWH)	Cost/season ($)	($/yr)	(yrs)
194,320	$19,431.96	123940	$12,394.05	$7,037.91	3.4

Attachment 1 - Flowserve Pump Curve



32.26

01-JUNE-2000
NEW SHEET

10EGH/10LKH

IMPELLER CURVES

All Specifications Subject to Change Without Notice.

Groundwater Catalog

Attachment 2

Variable Frequency Drive
Economic Analysis Data Collection Form

Field Office: ____________________________ Planner: ___________Job Class: _______
Landowner: ____ Date: ________________
Address: ____
Location: T/R/S: ____________________________ Block and Unit: _____________________
Field Name: _________________________________ Acres: __________________________

Pump Make: _______________________________ Model:___________________________
Age/condition of pump and motor, if known: ____
____
____
Motor HP: ______________________ Make: _______________________________________
Volts AC: __________ Phase: __________ RPM: ___________ Hertz: ______________

Annual Power Use/Season (KWH):______________ Cost/Season ($):_________________
Average Cost per KWH ($):____________ Estimated hours of use per year/season: ______

A VFD requires power to operate. In order for the VFD to provide a benefit by reducing power consumption, variations in pressure and/or flows during the season are necessary. Enter the estimated flow rates, pressures and time for each below in order to evaluate the benefit of the VFD.

Flow (gpm or cfs)	Pressure (psi)	Time (hrs or %)

Average Cost per KWH ($):____________________________________
Estimated Installation Cost of VFD ($): __________________________
Estimated Payback period of VFD (years): _______________________
Power Savings/yr ($/year):_______________________________________