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Operational energy-efficiency improvement of municipal water pumping in California

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ABSTRACT

This paper implements a normalization/regression-based approach to estimate the kWh energy and kW savings from an experimental OEEP (operational energy-efficiency program) for municipal water pumping in California. The voluminous 1-min data collected in the course of the OEEP presents a unique opportunity to analyze how VSD (variable-speed drive) technology aided by a PLC (programmable-logic-controller) may improve municipal water pumping's operational energy efficiency. Our proposed approach enables a comparison of pump operations with and without the OEEP, yielding accurate estimates for kWh energy and kW capacity savings that are useful in evaluation, monitoring, and verification of the program. Our findings lead us to conclude that (a) variability of efficacy by analyzed pump sites suggests targeted implementation of the OEEP; and (b) for a correctly-sized pump operating near its optimal kW-output value, adding a VSD and PLC can actually harm the pumping system's overall energy-efficiency.

1. Introduction

California's water pumping consumes approximately 1600 GWh, about 6% of the state's annual total consumption, suggesting its promising conservation potential [1,2]. Electricity savings can occur via water demand management [3,4]: reducing water consumption cuts water pumping and hence, its electricity use. Alternatively, electricity savings can occur via water supply management that encompasses leak detection and remedy, and replacing energy-inefficient equipment [5,6]. Another path is to improve the operational energy efficiency of water pumping, exemplified by the experimental OEEP (Operational Energy-Efficiency Program)[1] approved by the CPUC (California Public Utilities Commission) in 2010.[2]

The California OEEP has generated a large file of 1-min data on kW-output and kW-input collected during May 2010–August 2011. To fully utilize this voluminous and potentially noisy data file, however, requires an approach that can produce summary results useful in energy policy decision making. Our key findings are as follows. First, our normalization/regression-based approach enables a comparison of pump operations with and without the OEEP, yielding accurate estimates for kWh energy and kW capacity savings. Second, these estimates suggest targeted implementation of the OEEP, consistent with prior recommendations for the state's demand-side-management programs [7]. Finally, for a correctly-sized pump operating near its optimal kW-output level, adding a VSD (variable-speed drive) and PLC (programmable-logic-controller) can actually harm the pumping system's overall efficiency. This supports the recommendation for better pre-screening, technical assistance and post installation verification made by prior studies that have found measured savings lower than those predicted at several water pumping sites in California [8,9].

This paper makes three contributions. First, it analyzes an OEEP for municipal water pumping in California, the first VSD-PLC field experiment of its kind. Its results are immediately useful to energy and water utilities that wish to implement similar programs in their service areas. Second, it enriches the literature on electricity savings related to motor and pump and VSD technologies [e.g., Refs. [10–16]]. Third, it adds to studies published by this journal on the energy performance of VSD and control systems [17,18], and the energy-efficiency of motor systems in Europe [19], India [20] and the world [21]. Since the VSD-PLC technology considered herein

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[1] Note that a list of all acronyms and symbols used in this paper appears in Table 1.

[2] A description of this program is available at: http://www.cpuc.ca.gov/PUC/Water/oeep/

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has many industrial and commercial applications beyond municipal water pumping, we opine that operational energy-efficiency improvement deserves the attention of policymakers and exploration by energy researchers worldwide. Finally, it proposes a method for normalizing the operational requirements of VSD-PLC controlled pumps with fixed-speed drive pumps. Taken together, these contributions make the paper an original study in terms of data collection, real-world relevance, and methodology development.

This paper proceeds as follows. Section 2 describes the California OEEP. Section 3 presents our method for comparing pump operations and energy usage with and without the OEEP. Section 4 compares the OEEP's kWh and kW saving estimates obtained via a simple method and our method for four pumping stations. Finally, Section 5 concludes.

2. California OEEP

2.1. General description

The California OEEP aims to reduce the power consumption of a motor-pump system by replacing a pump run by a fixed-speed drive with a VSD. In addition, the OEEP installs a PLC, efficiency optimization software, and monitoring equipment at the facility to improve operational energy-efficiency.

A fixed-speed drive pump is only capable of running at full capacity; turning on and off to meet system demands. In contrast, the VSD controlled by the PLC continuously adjusts the motor speed to optimize the pump's output within the system constraints of pressure, level, and flow. Because of this difference in operation, a pump outfitted with a VSD and PLC is expected to run at a higher energy-efficiency than a fixed-speed drive pump, in spite of the fact that the addition of the VSD can reduce the system's energy efficiency by approximately 3% [22].

The monitoring equipment records real kW-input of the VSD-motor-pump combination at 1-s intervals, which are averaged to obtain 1-min data. It also records the pump's water flow in gallons per minute and pressure differential, or head, in feet. Flow and head can be converted into kW-output using

$$\mathrm{kW-output} = 1/5310 \times \mathrm{Flow} \times \mathrm{Head}. \quad (1)$$

We use the 1-min kW-input and kW-output data to compute the output/input ratio, to which we refer as WWE (wire-to-water efficiency).

To test if the OEEP improves a motor-pump system's WWE, the system was intended to be run in bypass mode once every eight days, thus ensuring that bypass mode did not repeatedly occur on the same day of the week. In bypass mode, electricity is provided to the motor through a separate parallel electrical circuit, using an across-the-line motor-starter. The VSD is not powered-up and the PLC and its control algorithm are inactive, causing the pump and motor to operate as if the pump has a fixed-speed drive. However, inconsistent implementation did not yield this systematic distribution of bypass days, necessitating our normalization approach detailed in Section 3.

2.2. Pump sites

Sponsored by the state's two largest electric utilities (Pacific Gas and Electric and Southern California Edison) and two water utilities (Alco Water Services and San Jose Water Company), the OEEP was implemented at five pump sites differentiated by pump type and HP (horse power). Owned by San Jose Water Company, the first two sites are:

- Grant Street Station, a vertical turbine type well pump operating at a groundwater production facility. The motor is a 200-HP premium efficiency model operating at 1750 RPM (revolutions per minute) and 480 VAC (volts alternating current), 3-phase. Design conditions are 2000 gpm (gallons per minute) at 300 feet head.
- Bascom Station, a horizontal centrifugal booster pump. The motor is a 75-HP premium efficiency model operating at 1750 RPM and 480 VAC, 3-phase; design conditions are 2000 gpm at 128 feet head.

Owned by Alco Water Company, the next three sites are:

- Alisal Well and County Well with vertical shaft turbine pumps, each driven by a 300-HP hollow shaft motor. The pumps are operated on pressure set points; the pump starts when pressure drops to a certain value. Shut down of the pump occurs when a set point of pressure is reached or a low frequency (Hz) condition exists.
- Hemingway booster pump that pumps from three underground storage tanks (12 feet deep), through a hydro-pneumatic tank, and into the distribution system. It operates on time of day, pressure, and tank level set points.

Our analysis below excludes the Hemingway pump because of the significant voltage imbalance on the main feeders during the OEEP test period. A voltage imbalance can damage the motor and, in this case, caused the VSD to operate at a degraded efficiency and power factor. As a result, the Hemingway pump's kW-input and kW-output data are not meaningful and are excluded from our WWE assessment.

3. Approach

A simple assessment of the program's WWE performance can be performed by computing an average WWE in bypass mode and

Table 1
List of acronyms and symbols used in this paper.

Acronym or symbol	Definition
OEEP	Operational energy-efficiency program
CPUC	California Public Utilities Commission
VSD	Variable-speed drive
PLC	Programmable-logic-controller
WWE	Wire-to-water efficiency
Y_t	WWE at time t
X_t	kW-output at time t
M_t	Binary indicator for VSD-PLC active
β_0	Intercept coefficient (includes binary indicators for month and hour)
β_1	Coefficient for kW-output
β_2	Coefficient for square of kW-output
θ_0	Coefficient for binary indicator for VSD-PLC active
θ_1	Coefficient for kW-output times binary indicator for VSD-PLC active
θ_2	Coefficient for square of kW-output times binary indicator for VSD-PLC active
ε_t	Random error term
D	Number of days of available data for a given pump
$\mathrm{kWh}_{\mathrm{out,avg}}$	Daily average kWh-output for a given pump
$\mathrm{kW}_{\mathrm{out},i}$	kW-output in minute i for a given pump
$\mathrm{kW}_{\mathrm{out},i,n}$	kW-output in minute i for a given pump in operational mode n
$\mathrm{kW}_{\mathrm{out,avg},n}$	Average kW-output level for a given pump in operational mode n
$\mathrm{kW}_{\mathrm{out,norm},n}$	Normalized kW-output level for a given pump in operational mode n
H_n	Normalized number of hours during which a given pump runs in operational mode n

comparing it to an average WWE with the VSD and PLC active. Seen in Table 2, this assessment offers an initial look at the WWE effect of the VSD-PLC activation. However, Table 2 does not account for the potential variations in WWE due to differing operational demands across days that may mask the actual energy and demand reductions that may occur.

Hence, we propose a normalization/regression-based approach to account for operational demand differences and create average usage profiles. This approach allows us to control for the influence of kW-output level and assess (1) if the VSD and PLC improve a motor-pump system's WWE, and (2) if the addition of the VSD and PLC translates into kWh and kW savings.

3.1. Regression

To answer the question of whether the VSD and PLC improve a motor-pump system's WWE, we assume that the WWE varies with the kW-output and VSD-PLC activation. We use the 1-min data for a given pump to create an empirical pump curve [23] by estimating the following regression with a quadratic specification:

$$Y_t = \beta_0 + \beta_1 X_t + \beta_2 X_t^2 + \theta_0 M_t + \theta_1 M_t X_t + \theta_2 M_t X_t^2 + \varepsilon_t \quad (2)$$

where Y_t = WWE at time t; X_t = kW-output at time t; and $M_t = 1$ if the VSD-PLC is active at time t, 0 otherwise. The random error ε_t appears in Eq. (2), reflecting that the quadratic specification is an imperfect fit of the recorded data. The coefficients to be estimated are (β_0, β_1, β_2, θ_0, θ_1, θ_2). Section 4 details our estimation process and results.

The quadratic specification of Eq. (2) matches a real-world pump curve that typically shows a pump's WWE to increase with kW-output until a WWE maximum is reached, at which point the WWE will begin to drop off with increasing kW-output levels. Additionally, the quadratic specification is a second-order approximation of any curve with unknown functional form and therefore provides a simple-to-execute estimation that still can offer a meaningful interpretation of results. For these reasons, we do not use other specifications (e.g., Translog, Generalized Leontief and Generalized Box-Cox) in Ref. [24] for our regression analysis.

Equation (2) implements the comparison of two WWE curves. To see this point, consider the expected WWE on a bypass-mode day

$$E(Y_t|M_t = 0) = \beta_0 + \beta_1 X_t + \beta_2 X_t^2 \quad (3a)$$

compared with the expected WWE on a VSD-PLC activation day

$$E(Y_t|M_t = 1) = (\beta_0 + \theta_0) + (\beta_1 + \theta_1)X_t + (\beta_2 + \theta_2)X_t^2. \quad (3b)$$

A comparison of Eqs. (3a) and (3b) implies that the WWE effect of VSD-PLC activation is

$$E(Y_t|M_t = 1) - E(Y_t|M_t = 0) = \theta_0 + \theta_1 X_t + \theta_2 X_t^2. \quad (4)$$

Equation (4) shows that the WWE effect is allowed to vary with the kW-output level, thus improving our understanding of the effect's dependence on kW-output.

We recognize the pump's WWE may have residual time-dependence not embodied in the kW-output level and VSD-PLC activation indicator. To account for time-dependence of Y_t, we assume the intercept β_0 is a linear function of binary indicators for time-of-day and month-of-year.

Table 2
Descriptive statistics for the 1-min data on kW-input, kW-output, and wire-to-water efficiency (WWE) by pump site.

Panel A. Grant Street Station (sample period: 1 May 2010–29 Aug 2011)						
Statistics	Bypass mode ($n = 36{,}450$)			VSD-PLC active ($n = 255{,}177$)		
	kW-input	kW-output	WWE	kW-input	kW-output	WWE
1st percentile	135.69	67.11	0.4434	87.97	6.58	0.0414
Mean	154.15	84.44	0.5502	128.26	72.84	0.5947
99th percentile	174.09	104.14	0.7608	177.44	93.11	0.7594
Standard deviation	18.02	13.22	0.0877	34.62	14.91	0.1268
Panel B. Bascom Station (sample period: 1 Aug 2010–4 Dec 2010)						
Statistics	Bypass mode ($n = 30{,}909$)			VSD-PLC active ($n = 134{,}484$)		
	kW-input	kW-output	WWE	kW-input	kW-output	WWE
1st percentile	61.62	36.42	0.5711	35.34	19.65	0.5441
Mean	63.08	37.46	0.5942	48.89	28.51	0.5829
99th percentile	64.17	38.16	0.6139	64.60	37.41	0.6061
Standard deviation	1.70	0.65	0.0231	7.82	4.66	0.0199
Panel C. County Well (sample period: 16 Aug 2010–27 Jul 2011)						
Statistics	Bypass mode ($n = 16{,}892$)			VSD-PLC active ($n = 268{,}182$)		
	kW-input	kW-output	WWE	kW-input	kW-output	WWE
1st percentile	120.30	74.66	0.6195	85.43	50.73	0.5879
Mean	121.45	79.21	0.6521	118.64	75.54	0.6362
99th percentile	122.82	82.19	0.6720	124.22	80.96	0.6609
Standard deviation	1.00	1.92	0.0136	8.32	6.13	0.0163
Panel D. Alisal Well (sample period: 3 May 2010–1 Feb 2011)						
Statistics	Bypass mode ($n = 4875$)			VSD-PLC active ($n = 96{,}848$)		
	kW-input	kW-output	WWE	kW-input	kW-output	WWE
1st percentile	204.62	133.83	0.6501	112.13	60.20	0.5330
Mean	205.51	143.79	0.6997	171.39	117.09	0.6779
99th percentile	206.88	149.53	0.7271	209.45	150.37	0.7445
Standard deviation	0.44	3.56	0.0172	29.13	24.80	0.0456

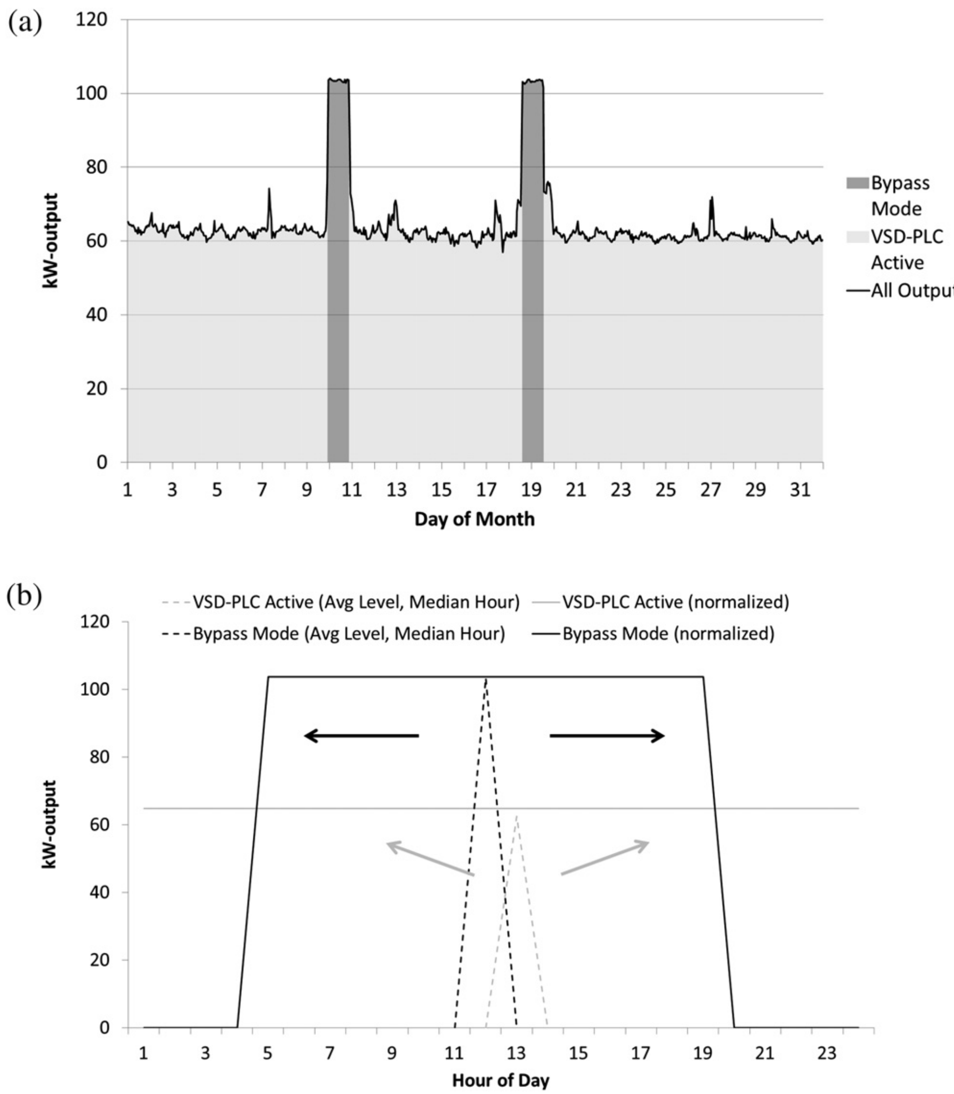

Fig. 1. Actual kW-output during July 2010 for Grant Street Station (a) and an example of the normalization process using this data (b). The high kW-output levels during bypass mode in (a) suggest that the pump is not operating under a comparable load to that of operation with the VSD-PLC active. Consultation with the San Jose Water Company staff suggests other nearby pumps taking on a heavier portion of the load when the VSD-PLC is active. However, the interconnectedness of the system makes it difficult to know which pumps may be taking on this extra load, and data is not available to analyze the system on a broader level. In (b), normalized daily profiles are created by scaling the average running level primarily along the time axis, but also along the kW-output axis as needed.

3.2. Normalization

After calculating the WWE regression, we estimate the average daily kW-input profiles to determine if the addition of the VSD and PLC translates into kWh and kW savings. This estimation, however, needs to account for the operational demand difference, shown in Fig. 1a, between the days when the VSD and PLC are active and the days when the pump is in bypass mode. We normalize to kWh-output, so that the output energy over a given period of time is maintained in bypass mode, or with the VSD and PLC active.

Table 3
Phillips–Perron unit root test statistics (*tau*) with number of lags are given in [ ] and *p*-value in ( ) for 1-min kW-input, kW-output and wire-to-water efficient (WWE) data series. The appropriate number of lags is automatically determined by the use of PROC AUTOREG.

Pump site	*Tau* with intercept			*Tau* with time trend		
	kW-input	kW-output	WWE	kW-input	kW-output	WWE
Grant Street Station	−13.4086 [108] (0.0010)	−33.4151 [108] (0.0010)	−25.1616 [108] (0.0010)	−20.7285 [108] (0.0010)	−38.5973 [108] (0.0010)	−32.0433 [108] (0.0010)
Bascom Station	−30.5296 [81] (0.0010)	−15.5310 [81] (0.0010)	−609.5397 [81] (0.0010)	−30.7421 [81] (0.0010)	−15.6439 [81] (0.0010)	−607.7095 [81] (0.0010)
County Well	−111.9464 [106] (0.0010)	−108.1135 [106] (0.0010)	−284.5132 [106] (0.0010)	−118.5440 [106] (0.0010)	−113.3285 [106] (0.0010)	−285.0466 [106] (0.0010)
Alisal Well	−32.3335 [63] (0.0010)	−34.1298 [63] (0.0010)	−154.7751 [63] (0.0010)	−32.9143 [63] (0.0010)	−35.0220 [63] (0.0010)	−160.5265 [63] (0.0010)

Table 4
Robust regression results by pump site. For brevity, this table does not report the coefficient estimates for the binary indicators that are used to capture the time-dependence of the WWE. All coefficient estimates in this table are statistically significant at the 1% level, except for the two noted by "*".

Variable (coefficient)	Grant Street Station	Bascom Station	County Well	Alisal Well
Sample size	291,627	165,393	285,074	101,723
R^2	0.7267	0.4027	0.4953	0.6166
Intercept (β_0)	−3.746	0.01454	−0.1150	−0.05256*
X_t: kW-output (β_1)	0.09142	0.009773	0.01583	0.005466
X_t^2: kW-output squared (β_2)	−0.0004777	0.0001519	−0.00007590	−0.000003226*
D_t: VSD-PLC active indicator (θ_0)	3.790	0.3220	0.6410	0.2407
$D_t X_t$: VSD-PLC active indicator × kW-output (θ_1)	−0.08052	0.006872	−0.01383	0.001411
$D_t X_t$: VSD-PLC active indicator × kW-output squared (θ_2)	0.0004239	−0.0004259	0.00007058	−0.00002157

We normalize to an average 24-h period, with a step size of one hour using the following steps:

Step 1. Use the 1-min kW-output data to estimate the pump's average daily kWh output for the entire sample period. We compute the daily output kWh as

$$\text{kWh}_{\text{out,avg}} = \sum_i \text{kW}_{\text{out},i}/D, \tag{5}$$

where the index i runs across all minutes of available data, and D is the total number of days of available data. Note that this sums indifferently over periods of both *bypass mode* and with the *VSD and PLC active*. This average daily kWh output level serves as the output target that the pump must achieve each day.

Step 2. Find the average running level of the pump in each operational mode. We calculate

$$\text{kW}_{\text{out,avg},n} = \sum_i \text{kW}_{\text{out},i,n}/\sum_i n_i, \tag{6}$$

where the index n indicates *bypass mode* or *VSD and PLC active*. As is demonstrated by the different operating levels in Fig. 1a, these values will be decidedly distinct.

Step 3. Determine the number of hours per day during which the pump must run in order to meet the daily output target found in step (1) using[3]

$$H_n = \left\|\text{kWh}_{\text{out,avg}}/\text{kW}_{\text{out,avg},n}\right\| \wedge 24. \tag{7}$$

For *VSD and PLC active* operations, H typically equals 24, indicating that the pump runs all day. For *bypass mode*, H often equals less than 24, implying that the pump runs for fewer hours.

Step 4. Scale along the kW-output axis to exactly match normalized kWh-output levels. This is necessary because we are capped at 24 h in a day and are otherwise rounding to the nearest hour in Eq. (7). This step scales continuously using

$$\text{kW}_{\text{out,norm},n} = \text{kW}_{\text{out,avg},n} \times \text{kWh}_{\text{out,avg}}/\left(\text{kW}_{\text{out,avg},n} \times H_n\right). \tag{8}$$

Due to the scaling done along the time dimension in step (3), the adjustment made in Eq. (8) for *bypass mode* will be very small and within the boundaries of the pump's operational abilities. Frequently, this same principle limits the adjustment of $\text{kW}_{\text{out,avg},n}$ levels with the *VSD and PLC active* as well, but the cap of 24 h means that this scaling will occasionally be more significant.

[3] In Eq (7), "$||x||$" means the nearest integer to x, and "$x \Lambda y$" means the minimum of x and y.

Step 5. Determine the specific hours during which the pump is running in *bypass mode* and with the *VSD-PLC active*. To do this, we expand evenly around the median hour of all data points for each operational mode until the pump is running for H_n hours. We note here that the pumps, when running in *bypass mode*, are characterized by running for several hours at a time and not frequent starting/stopping. As such, it is a reasonable estimation of *bypass mode* operations to create a normalized hourly kW-output profile that only turns on and off once per day.

An example of this process using actual July data from the Grant Street Station is shown in Fig. 1b. Using the estimated regressions, and the daily profiles resulting from the normalization process, we compute the kW-input profiles for each operational mode. For each hour, the kW-output level is divided by the regression-estimated WWE, which is calculated based on the kW-output level, mode of operation, and temporal factors, to attain kW-input profiles.

The estimated kW-input profiles allow us to compute the OEEP's performance metrics in a counter-factual setting, requiring each pump with the VSD-PLC active to do the same work as would have been done absent the VSD-PLC. Other metrics include WWE improvement (=WWE difference due to VSD and PLC) and kW savings (=maximum input-kW difference due to VSD and PLC).

4. Results

4.1. Descriptive statistics

Table 2 displays the descriptive statistics for the 1-min kW-input and kW-output data by pump site. These statistics show that the bypass mode levels of input- and output-kW are consistently higher than the VSD-PLC active mode levels. Additionally, the VSD-PLC active mode levels of kW-input and kW-output show considerably more variability than those of the bypass mode, indicating the flexibility added by the VSD-PLC combination. However, the WWE shows less variability than the kW-input and kW-output values due to the PLC seeking a consistent efficiency level.

Also included in Table 2 are the simple averages of WWE for each pump. This simple calculation indicates (a) a WWE improvement of 0.0445 with the OEEP at Grant Street Station; and (b) WWE degradations of 0.0113, 0.0159, and 0.0218 at Bascom Station, County Well, and Alisal Well respectively. Though three of the four sites show efficiency degradation in this simple assessment, it is worth noting that the lower kW-input levels with the VSD-PLC active imply savings of 26, 14, 2.8, and 34 kW of demand at Grant, Bascom, County, and Alisal respectively.

4.2. Regression results

Using 1-min high frequency data to analyze WWE presents may lead to spurious results when the data series are non-stationary,

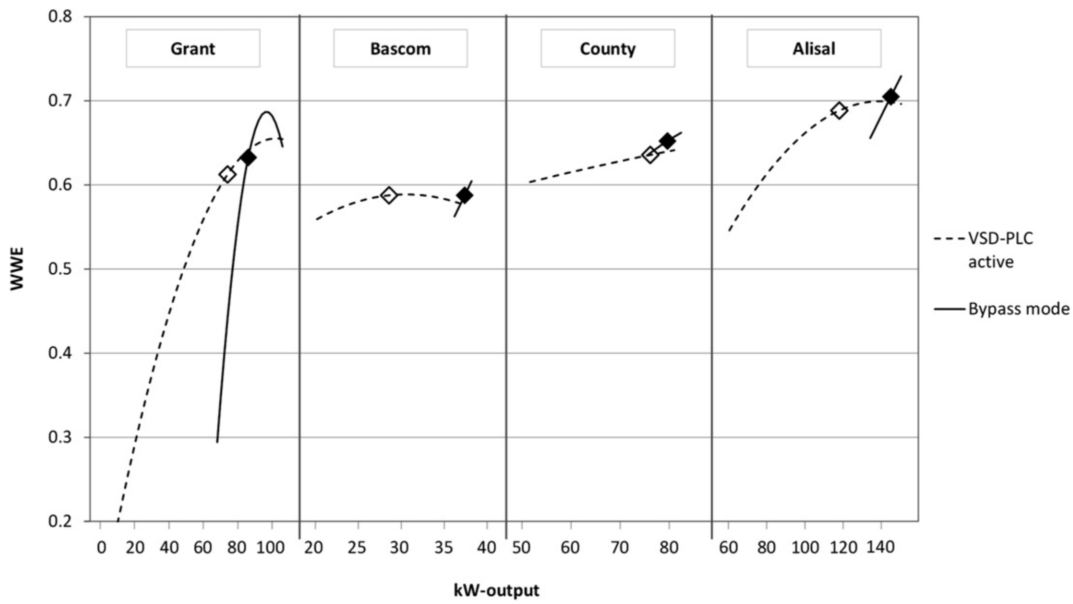

Fig. 2. Empirical pump curves by site with VSD-PLC active and in bypass mode. The curves are drawn over the observed 1st percentile to 99th percentile operating range observed during the analysis period for each pump/mode of operation. The diamonds indicate the average operating level observed with VSD-PLC active (unfilled) and in bypass mode (filled).

Table 5
Performance metrics by pump site. WWE improvement = WWE in bypass mode − WWE with VSD-PLC active; and WWE %change = WWE improvement/WWE in bypass mode. The kWh and kW savings and their %changes are computed in the same manner.

Pump site	Mode	Daily output kWh	Daily input kWh	Daily max kW-input	WWE	Daily kWh saving (%change)	Daily kW saving (%change)	WWE improvement (%change)
Grant Street	Bypass	1721	3024	154	0.569	–	–	–
	VSD-PLC active	1721	2987	128	0.576	36 (1.2%)	25 (16.6%)	0.007 (1.2%)
Bascom	Bypass	657	1127	64	0.583	–	–	–
	VSD-PLC active	657	1118	49	0.588	8.8 (0.8%)	14 (22.6%)	0.005 (0.8%)
County	Bypass	1260	1943	121	0.648	–	–	–
	VSD-PLC active	1260	1980	119	0.636	−37 (−1.9%)	2.4 (2.0%)	−0.012 (−1.9%)
Alisal Well	Bypass	906	1271	207	0.713	–	–	–
	VSD-PLC active	906	1336	168	0.678	−65 (−5.1%)	39 (18.8%)	−0.034 (−4.8%)

following a random walk. Hence, prior to estimating Eq. (2), we perform the Phillips–Perron unit root test [25] to ensure that the 1-min data series are stationary. Obtained by running PROC AUTOREG in SAS (statistical analysis system) [26], the test results in Table 3 reject ($\alpha = 0.01$) the null hypothesis that a time series has a unit root, implying that the data series are stationary, and unlikely to cause spurious regressions [[27], Chapter 19].

We use the robust regression method [28] to estimate Eq. (2), thus ensuring that the coefficient estimates are not unduly influenced by possible outliers in the noisy 1-min data.[4] Table 4 reports that the regressions have adjusted R^2 values of 0.40–0.73, indicating that they explain 40%–73% of the WWE's variance. These adjusted R^2 values suggest that Eq. (2), though simple and parsimonious, can reasonably fit each pump site's very large data file of 200K to 300K observations. Besides two exceptions at the Alisal Well, all coefficient estimates are significant at the 1% level, lending support to the quadratic specification of Eq. (2).

4.3. Pump curves

We use the coefficient estimates in Table 4 to generate the empirical pump curves shown in Fig. 2. The narrow kW-output operating range and steep slope of the WWE curves in bypass mode reveal the pumps' inability to run at levels other than full capacity. Meanwhile, the VSD-PLC active curves cover a wider kW-output range and drop off less steeply, indicating the pumps' ability to run efficiently over a wide range of kW-output levels. However, we note that the majority of each VSD-PLC curve lies below the WWE value associated with the bypass mode average kW-output level.

4.4. Performance metrics

Here we determine if the addition of the VSD and PLC translates into kWh and kW savings; the second question poised above. Using the multi-step process described in Section 3.2, we compute the average daily kWh, kW, and WWE and display the results in Table 5. This table shows WWE improvements of 0.007, and 0.005 for Grant Street Station and Bascom Station respectively, along with WWE degradations of 0.012 and 0.034 for County Well and Alisal Well respectively. These estimates differ from those based on Table 2, indicating that accounting for operational demand differences matters in estimating the WWE effect of the OEEP.

The kWh savings estimates in Table 5 closely mirror the WWE improvement estimates. Moreover, all four sites show kW savings due to VSD-PLC activation, confirming the finding based on Table 2.

5. Conclusion

The normalization and regression approach employed here to compare the operational efficiency of pumps in different control-modes is widely applicable to other pumping efficiency programs

[4] This is done by running PROC ROBUSTREG in SAS [29].

and VSD applications where different operational requirements may mask program savings determinations. Indeed, the approach adopted herein has enabled an accurate determination of the effect of the VSD-PLC on pump efficiency, kW demand, and kWh energy consumption.

Our empirical findings lead us to conclude that a program designed to improve municipal water pumping's operational energy efficiency requires targeted implementation, aiming at pump sites with known poor performance or pumps with variable operating regimes. For pump sites consistently operating near their optimal kW-output values, adding VSD-PLC does not yield substantial WWE improvement and can actually harm overall system efficiency. Post installation measurement and verification is therefore critical to ensure that a targeted implementation is achieving the desired results.

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