The Search for Energy Savings: Optimization of Existing & New Pumping Stations

Chris Reinbold and Vincent Hart

Water and wastewater treatment operations account for 30 to 50 percent of all municipal power use—the largest single consumption purpose of municipal power. Approximately 90 percent of power used at water treatment facilities is attributed to pumping. Pumping systems also consume a large fraction of the power use at a wastewater facility.

Pumping systems account for 3 percent of the total annual power consumption in the United States (Engle, 2008). The typical power breakdown at a water treatment facility is shown in Figure 1. This figure reinforces the concept that the overwhelming majority of power used by water treatment facilities is for pumping.

The uses of power at water/wastewater treatment facilities impact the entire power distribution system and generation system. Increases in power rates are highly dependent upon the increase in power demand and peak power demand over time. One item that is typically forgotten is the fact that power generation and delivery systems are inefficient. For every 9.5 units of hydraulic energy that are utilized to pump water, it takes 100 units of energy generated at the power facility, as shown in Figure 2.

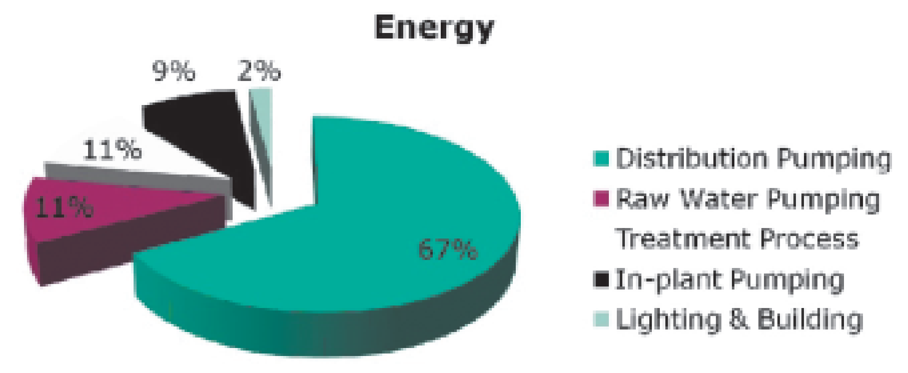
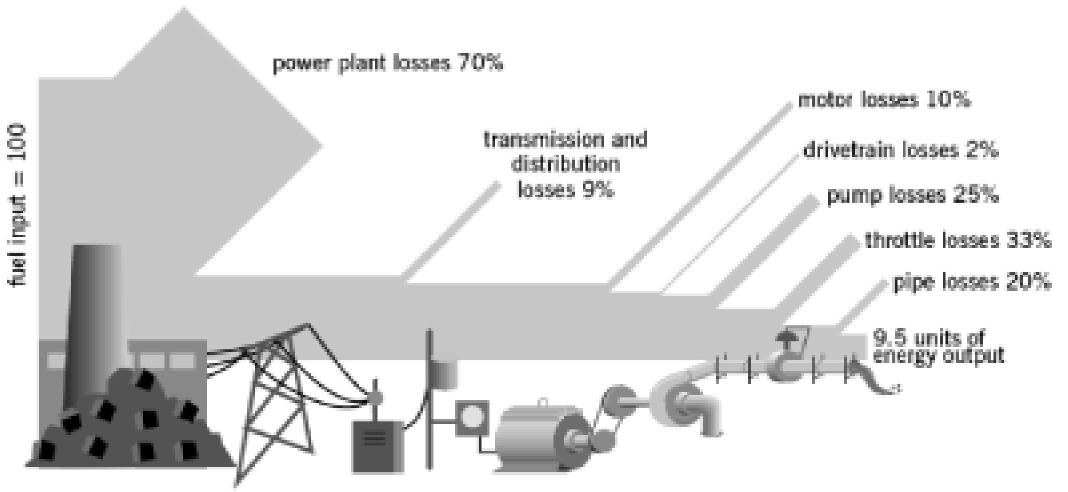


Figure 1: Typical Energy Use at a Water Treatment Facility



From the *Drivepower Technology Atlas*. Courtesy of E SOURCE, www.esource.com.

Figure 2: Power Losses from Generation through End Use (Pumping)

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Pump Selection

The typical approach to the design of pumping systems includes the following factors:

- Minimum Pump Station Flow Rate
- Average Pump Station Flow Rate
- Maximum Pump Station Flow Rate
- Type of Fluid Pumped
- Total Dynamic Head (TDH)
- Available Pumps

The TDH is determined from a number of factors, which include:

- Friction Losses in the System
- Static Head Differences
- Water Temperature
- Age and Conditions of the Pipe (and future conditions)
- Flow Control

Typically, pump stations are designed considering only the conditions at the maximum pump station flow rate (design point). Unfortunately, this approach focuses on conditions that are met only 1 percent of the time. The other 99 percent of the time, the system is operating under different conditions, so this design approach results in poor efficiencies during most operating conditions.

This approach to design and construction of pump stations also lends itself to conservative pump sizing. The distribution system modeler adds a level of conservatism, the designer adds a level of conservatism, and finally the pump manufacturer adds a level of conservatism. This approach typically will meet the delivery of the maximum amount of water without any problems, but it adds to the inefficiency during normal operations.

As engineers, we historically have been judged on whether the system can deliver what it is supposed to instead of its energy efficiency. Many times the design conditions (maximum flow rates) will not be met for five or 10 years—or longer.

One of the ways to address this difference between the traditional method of design and an energy-efficient approach to design is to examine the operating conditions over the entire range of operation, with an emphasis on the average or normal operating conditions. Understanding the range of flows and heads in combination with each other is critical to an energy-efficient design. Over the years, the use of variable frequency drives has provided us with a great tool for operational flexibility but has resulted in a tool that has "routinized" our designs and has reduced the energy efficiency of our pump stations.

The design of a pump station is dependent upon our ability to understand the operating conditions and to tailor the design to match the demands of the system. For example, a system where the TDH changes drastically from summer to winter may require pumps with a wider range of higher efficiencies and the use of variable frequency drives. If the system head curve (change in discharge pressure with increased flow) is flat and not dependent upon the flow rate leaving the pump station, or the static elevation on the suction and the discharge do not change over time, then pumps with a higher best efficiency point (without a wide range of higher efficiency) and constant speed motors will be the best fit from an energy-efficiency perspective.

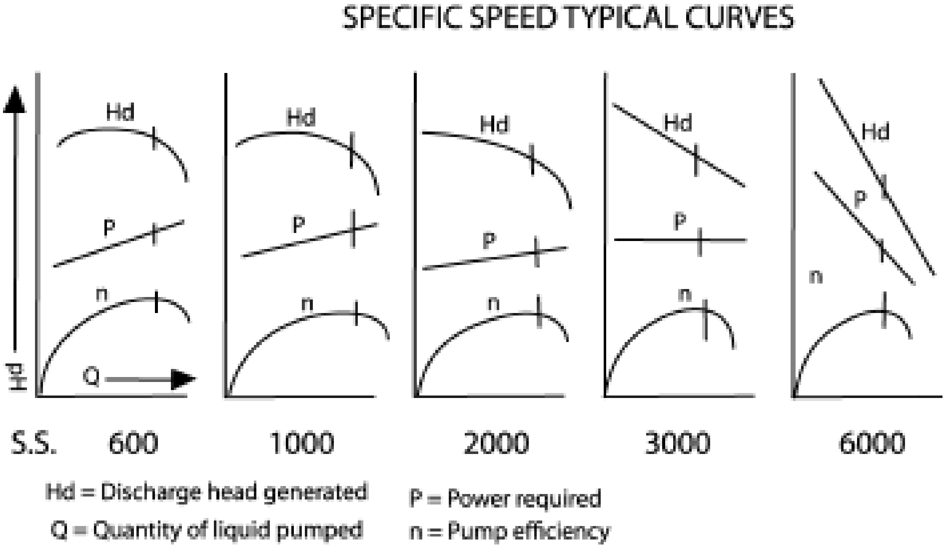

Figure 3: Impact of Changing Specific Speed on Pump Curve and Efficiency Characteristics (courtesy McNally Institute)

One of the tools that can be used to assist with pump station design and pump selection is specific speed. The specific speed describes the geometry of the pump impeller. The formula for specific speed is:

$$\text{Specific Speed } (N_s) = \frac{NQ^{1/2}}{H^{3/4}}$$

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Where:

- Ns = Specific Speed (no units)
- N = Speed in revolutions per minute (rpm)
- Q = Flow in gallons per minute (gpm)
- H = Head in feet (ft)

The specific speed can be used for the following:

- Select the shape of the pump curve
- Determine the efficiency of the pump
- Anticipate motor overload
- Predict NPSH requirements
- Select the lowest pump cost for the application

High specific speeds indicate more axial flow (flow generating) characteristics and lower specific speeds indicate more radial flow (pressure generating) characteristics. In general, the efficiency at the best efficiency point increases as the specific speed increases.

Also as the specific speed increases, the steepness of the pump curve increases. As the specific speed decreases, the flow range of higher efficiencies increases for the pump. These characteristics can assist the design engineer with tailoring the pump station for energy efficient design. Figure 3 shows the impact of changes in specific speed on these factors.

The cost to operate the pump over 20 years typically far exceeds the capital cost of the pump. The following example demonstrates:

- Design Flow Rate = 5,373 gpm
- Total Dynamic Head = 280 feet
- Horsepower = 500 HP

The capital cost of this pump was $65,000 (2004 dollars). The utility was paying $0.05 per kilowatt hour and was operating the pump 24 hours a day for seven days a week, resulting in a power cost of $1.89 million over a 20-year period. The power cost associated with the operation of the pump is 30 times more than the capital cost of the pump. This is approximately $24,500 per point of hydraulic efficiency of the pump.

As an industry, typically we find three pumps that are close to each other in efficiency at the design point. We bid these pumps against each other on bid day without any consideration of the differences in efficiency. As an industry, we need to move toward the evaluation of pumps based on the net present value of the pump over its life.

It should be recognized that the cost of the pump does not correlate to the energy efficiency of a pump, so typically the owner will not need to pay a premium for a higher-efficiency pump.

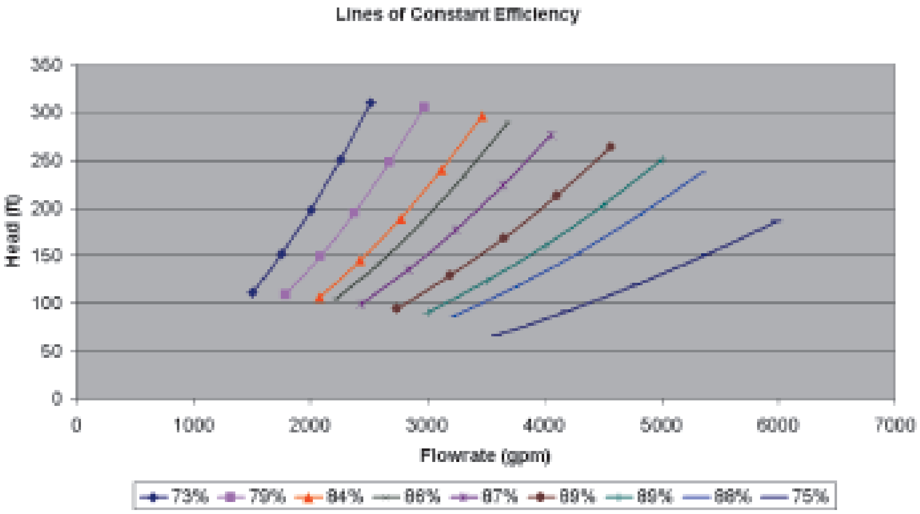

Figure 4: Plot of Lines of Constant Efficiency of a Pump

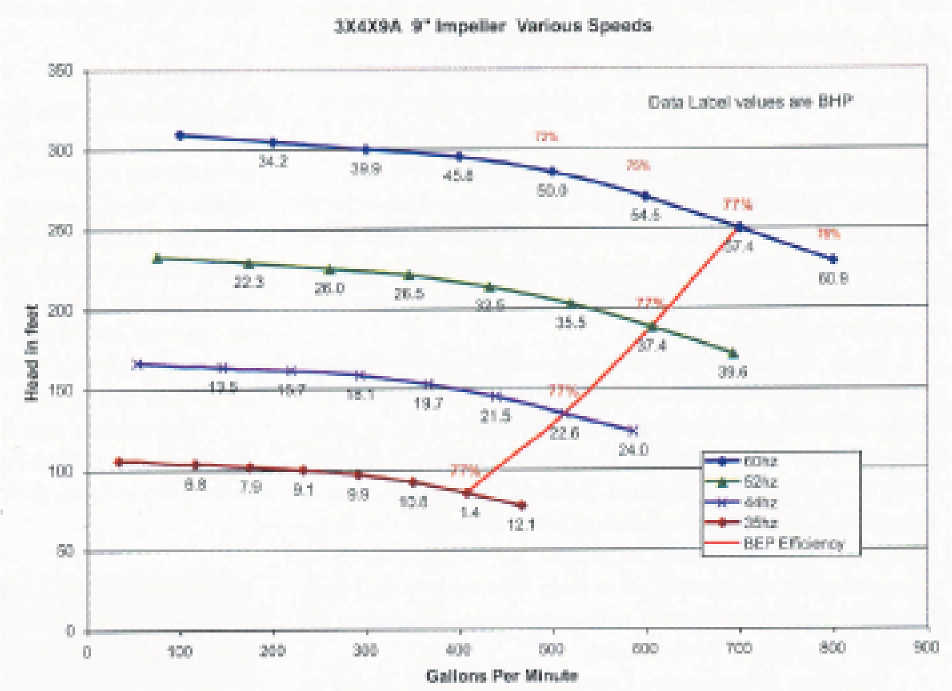

Figure 5: One of the Challenges Associated with VFDs is the Flattening of the Pump Curve (see the low speed curves)

Variable Frequency Drives

Variable frequency drives (VFDs) allow the speed of a pump to turn down, resulting in reduced flow rates and corresponding lower TDHs. VFDs have been used (and misused) as a tool to provide more operational flexibility. Most of the time no consideration is given to the fact that there are efficiency losses associated with their use. Hydraulic gains in efficiency must counterbalance the electrical efficiency losses of using a VFD unless operational considerations dictate its use—such as very tight flow control requirements.

Depending on the loading of a VFD, the efficiency loss can range from 4 to 10 percent. At 100 percent of the rated load (horsepower), the electrical efficiency losses are approximately 4 percent. At 50 percent of the rated load (horsepower), the electrical efficiency losses are approximately 10 percent.

Although the use of VFDs should be considered carefully, the hydraulic benefits can outweigh the electrical inefficiencies. The affinity laws are one tool used to determine this. These are laws which dictate the changes in flow rate, head, and horsepower as the speed of the pump is decreased. The best efficiency point tracks with the affinity laws and allows the design engineer to track the best efficiency

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point of the pump at reduced speeds. The affinity laws are:

$(RPM_2 / RPM_1) = (GPM_2/GPM_1)$

$(RPM_2 / RPM_1)^2 = (HEAD_2/HEAD_1)$

$(RPM_2 /RPM_1)^3 = (BHP_2/BHP_1)$

This means that a 4,500-gpm pump (at its best efficiency point) when turned down to 70-percent speed becomes a 3-200-gpm pump (at its best efficiency point). By plotting the lines of best efficiency, the design engineer can understand the impacts of turning down the pump. Plotting lines of constant efficiency is shown in Figure 4. The top point on each line of constant efficiency represents all the points associated with the original pump curve (operation at 100-percent speed).

Another challenge with VFDs is the fact that pump curves will flatten out at low speeds and can result in operational challenges. This flattening of the pump curve is demonstrated in Figure 5.

If variable speed pumps are to be used for a pumping system design, it is proposed that the operating efficiency and range of efficiencies should dictate the number of pumps used in the design of the pump station. The following example shows the impact of the number of pumps on the overall operating efficiency of the pump station. The example consists of the following assumptions:

- The maximum flow rate of the pump station is 30 million gallons per day (mgd).
- The average flow rate of the pump station is 15 mgd.
- The minimum flow rate of the pump station is 10 mgd.
- The discharge pressure is maintained at 100 pounds per square inch (psi) at any discharge flow rate (flat system curve).
- The efficiency characteristics of the pumps are exactly the same (shape of curve and efficiency). The only difference is that they are scaled up or down, depending on the desired size of the pump. This way an apples-to-apples comparison can be made.

Based on these assumptions, an analysis was done for different numbers of pumps to determine the optimal number of pumps to achieve a high level of efficiency, assuming that each pump was provided with a VFD. The best efficiency point coincided with the design point to provide a comparison with a typical pump station design scenario. The pump scenarios were:

- One pump – 30 mgd each at 100 psi TDH
- Two pumps – 15 mgd each at 100 psi TDH
- Three pumps – 10 mgd each at 100 psi TDH
- Four pumps – 7.5 mgd each at 100 psi TDH
- Five pumps – 6 mgd each at 100 psi TDH

The pump scenarios were analyzed to determine the efficiency at the minimum flow (10 mgd), the maximum flow (30 mgd), the average flow (15 mgd) and the worst-case efficiency over the entire operating range of the pumps. All pumping scenarios could cover the 10 to 30 mgd operating range without running too far off the curve or too far back on the curve.

The efficiency for one pump operating ranged from 66 percent hydraulically efficiency at 10 mgd to 84 percent hydraulic efficiency at 30 mgd. The minimum hydraulic efficiency was 66 percent (which corresponded to the minimum flow rate).

As more pumps are added to the pump station, the minimum efficiency increases significantly from 66-percent hydraulic efficiency for one pump to 78-percent hydraulic efficiency for two pumps. With three pumps, the minimum hydraulic efficiency is up to 81 percent. For pump station designs with four or five pumps, the hydraulic efficiency is limited by the efficiency of the design point (84 percent) and is the point of diminishing returns for hydraulic efficiency.

Figure 6 shows the efficiency for each of the pump station options at minimum, aver-

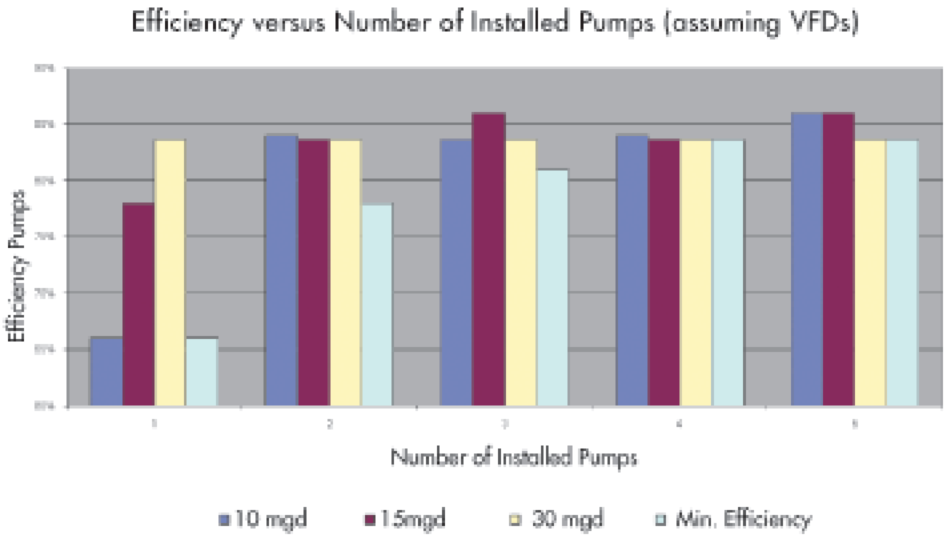

Figure 6: Hydraulic Efficiency Versus the Number of Pumps (assuming all pumps have VFDs)

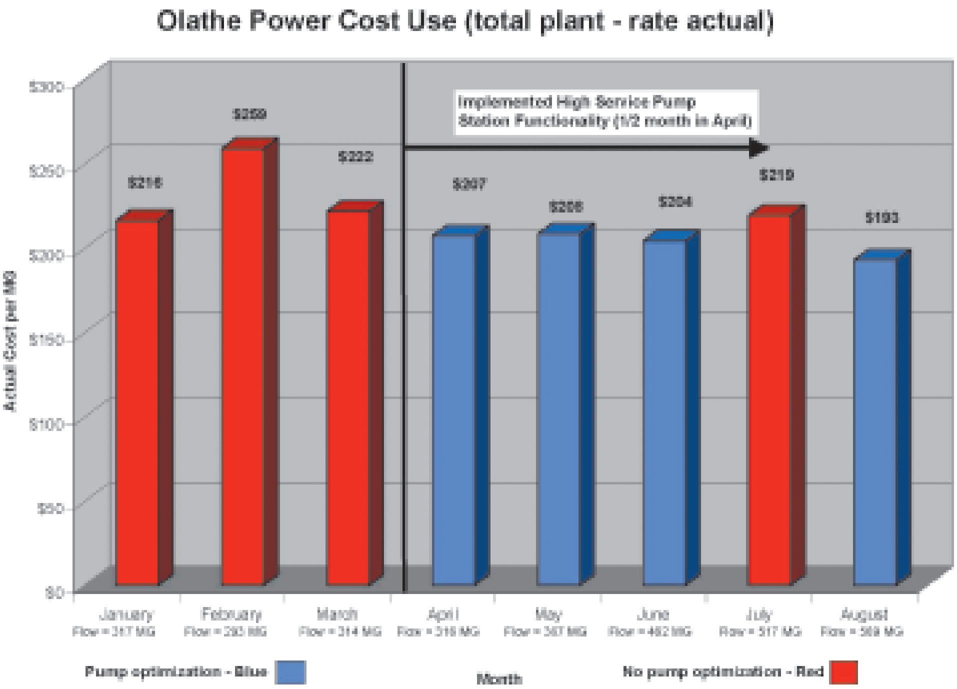

Figure 7: System Operation with the Pump Control Algorithm versus Manual Operation (No Pump Optimization)

age, and maximum flow rates, as well as the worst-case efficiency.

In addition to hydraulic efficiency is the electrical efficiency aspect. The speed with one pump operating at the minimum flow rate is approximately 78 percent speed. At this speed, the load on the VFD is approximately 50 percent of the rated load. This means that the efficiency of the VFD is approximately 90 percent. The following are the minimum combined efficiencies (hydraulic efficiency times electrical efficiency) for each pump scenario:

- One pump – 59 percent (66 percent times 90 percent)
- Two pumps – 71 percent (78 percent times 91 percent)
- Three pumps – 75 percent (81 percent times 92 percent)
- Four pumps – 78 percent (84 percent times 93 percent)
- Five pumps – 79 percent (84 percent times 94 percent)

This method of pump station design was utilized for a pump station for the city of Olathe, Kansas. Five high-service pumps were utilized and are comparable to the example, except they covered much larger TDH conditions (from 78 to 128 psi discharge pressures). The affinity laws and the best efficiency point were utilized to develop an algorithm for pump control (programmable logic controller-based).

The algorithm was based on operating the best combination of pumps based on the TDH conditions (discharge system pressure). This algorithm still allowed the operations staff to control and dictate the amount of flow coming from the high-service pump station, but it also made the station as efficient as possible for the operator-dictated conditions.

A graph was created which showed the power costs per million gallons of water pumped (y-axis) versus the month of operation (x-axis). The graph starts during months without the algorithm, and then the algorithm is turned on in the month of April (halfway through the month). The algorithm is shut off during the month of July and then turned back on during the month of August.

Based on this data, the algorithm is anticipated to save the city of Olathe 10 percent when the algorithm is operating versus a manual operator-controlled scenario. Figure 7 shows this graph.

The algorithm also provided other beneficial automation features, such as controlling the number of start/stops on a motor and preventing the operation of a pump too far out or back on its pump curve.

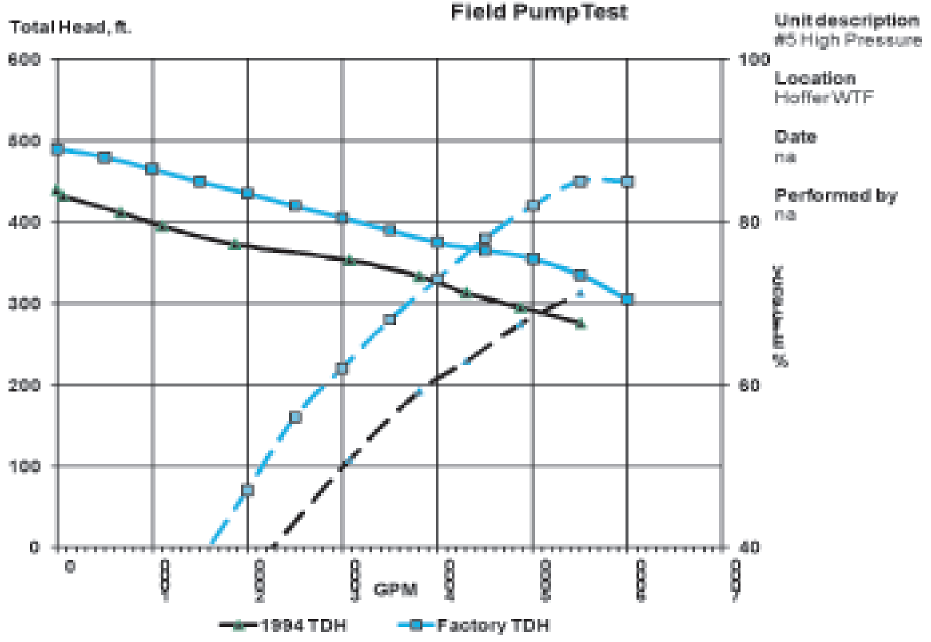

Figure 8: Comparison of Original and Current Pump Curves
(courtesy Fayetteville Public Works Commission, Fayetteville, North Carolina)

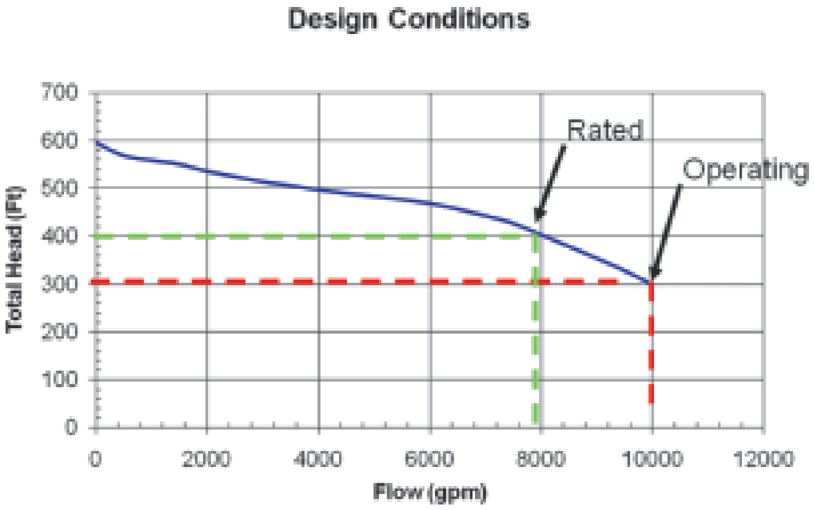

Figure 9: Comparison of Original Design Point (Rated) Versus the Current Operating Point

Pump Checkup

Over time, pumps wear and performance degrades. Testing the current pump curve versus the original pump curve provides the opportunity to improve performance of the existing pump without waiting for a significant mechanical problem to occur. This process consists of measuring the flow rate and TDH across a range of conditions, as well as the power draw (kW).

Typically the pump is tested from shutoff (no flow) out to 125 percent of the flow rate associated with the best efficiency point. Once this process is complete, the current pump curve can be compared to the original pump curve in order to determine whether the pump should be rehabilitated.

Figure 8 shows an original pump curve and currently operating pump curve for a high-service pump for Fayetteville Public Works Commission in Fayetteville, North Carolina. From the attached figure, it can be seen that the pump has lost approximately 500 gpm at the design point and 13 percent efficiency over time.

Using the original efficiency and flow rate as well as the typical operating time of the pump (eight hours per day), the Public Works Commission is able to compare energy lost to the cost of the pump repair/rehabilitation to determine the payback. For this pump, the payback was 2.8 years and based on this analysis was sent out for repair.

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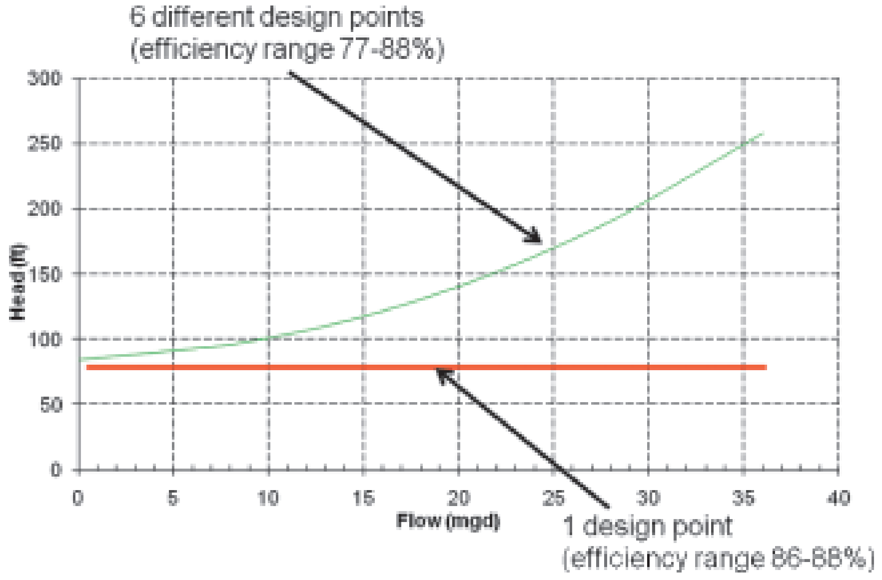


Figure 10; Comparison of a System Curve with High Friction Loss and a Flat System Head Curve

Figure 11: Approach to Evaluation an Existing Pump Station

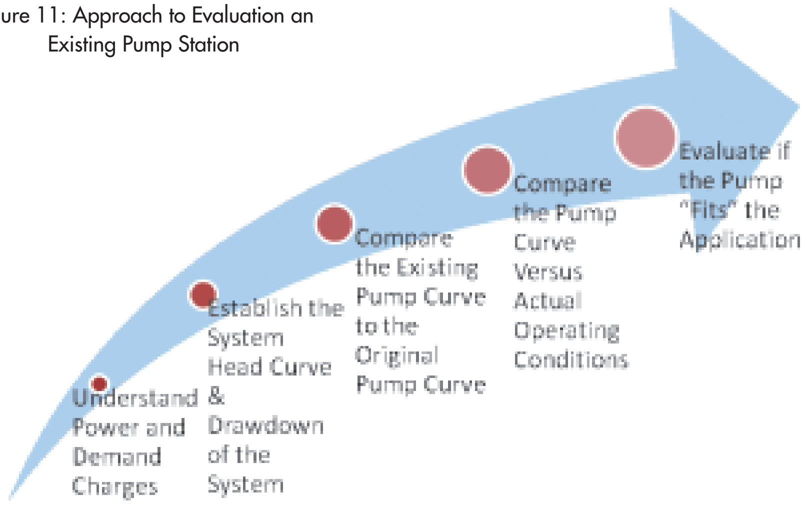
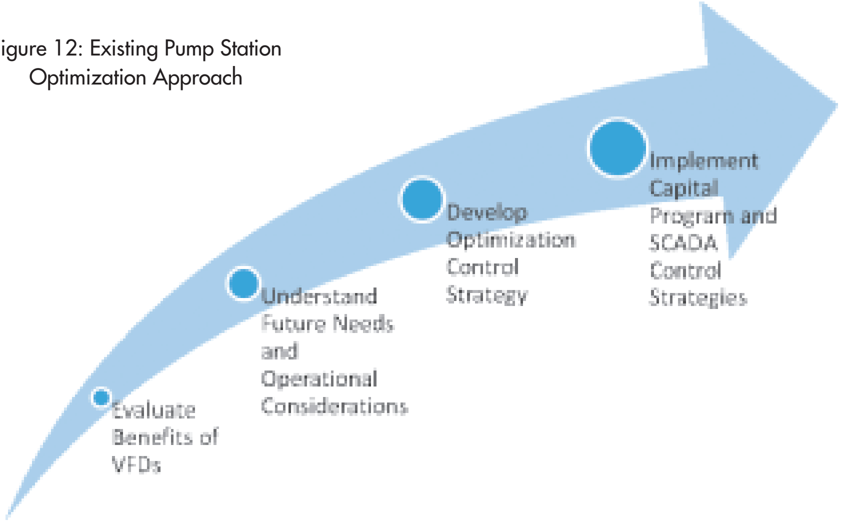


Figure 12: Existing Pump Station Optimization Approach



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Checking the Original Design Point

Checking what the pump currently is doing versus the originally purchased pump is important, but equally important is checking where the pump currently is operating versus the original pump design point. As discussed previously, many added layers of conservatism contribute to the system head curve, and the method of pump design leads to pumps that are running out on their curve and are oversized for the application.

Examining the current operating point and comparing it to the design point allow a re-examination and potential opportunity to modify the pump to accommodate the actual operating point(s).

Figure 9 shows a pump curve with the original design point, as well as the actual operating point (the operating point was consistent year round). The original design point was 8,000 gpm at 400 feet of TDH. The actual design point was 10,000 gpm at 300 feet of TDH. During routine maintenance/rebuild of this pump, the bowls were modified to lower the pump curve so that the best efficiency point (85 percent) matches the current operating point.

Pump Efficiencies Impact on Maintenance

One of the usually overlooked facets of pumps and pump design is the impact of hydraulic efficiency on the long-term wear and maintenance associated with pumps. A pump with a high hydraulic efficiency transfers the energy applied to the pump where you want it: to the water. Inefficient pumps transfer energy to the pump, which is where you don't want it (such as bearings, seals, etc.), resulting in more maintenance and faster degradation in pump performance.

Motors

Motors and motor efficiency are much more forgiving over a wide operating range than the pump or the VFD that might be used. An example medium voltage motor has the following efficiencies at different motor loads:

- Full Load – 95.2 percent efficient
- 3/4 Load – 95 percent efficient
- 1/2 Load – 94.8 percent efficient

One of the potential problems associated with motor efficiency is the rewind process. Many times motor rewind changes the efficiency and degradation occurs because of the rewind procedures. Most utilities demand motors to be rewound quickly, which is counterproductive when compared to maintaining the

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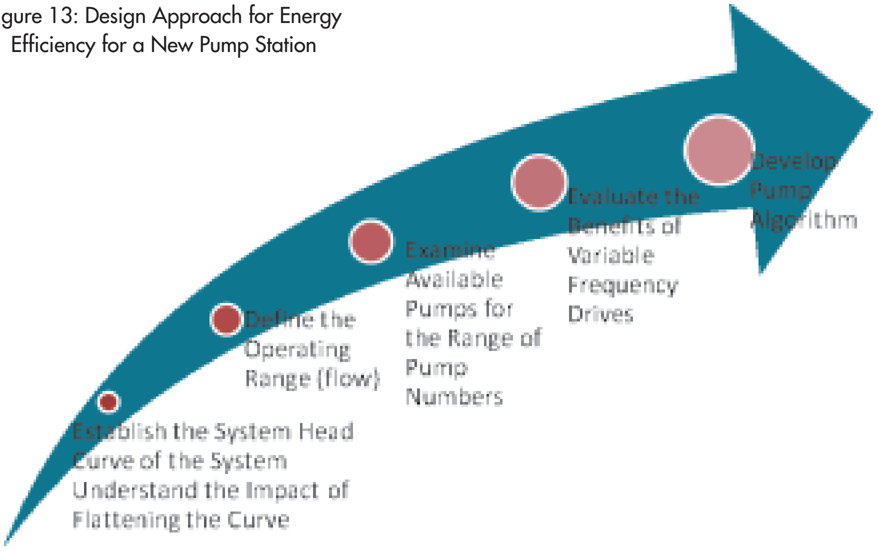
Figure 13: Design Approach for Energy Efficiency for a New Pump Station



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original efficiency of the motor. An unchecked motor rewind can lose as much as 5 percent of motor efficiency. Because of this situation, the rewind shop should be required to guarantee no degradation in motor efficiency.

Pump Systems

This article already has discussed that the level of conservancy of pump design typically results in oversizing of pumping equipment. The design of the system into which a pump discharges is usually analyzed by comparing the cost of the energy used to pump the water versus the cost of the piping system. This is the wrong approach to system design and does not consider the sizing and cost of all the equipment that must be supplied.

If the piping system is designed to minimize friction loss, this results in a flatter system head curve. The resulting system results in a lower TDH and reduces the size of the pump and associated equipment. The following is a list of all equipment that may be downsized if the friction loss is minimized and the system head curve is flattened:

1. Motor Size
2. Structural pad size
3. Disconnect size
4. Conduit size from motor to variable speed drive
5. Wire from motor to variable speed drive
6. Size of the variable speed drive
7. Conduit size from the variable speed drive to the switchgear
8. Wire size from the variable speed drive to the switchgear
9. Switchgear size
10. Conduit size from the switchgear to the transformer
11. Wire size from the switchgear to the transformer
12. Transformer size
13. Wire size from the transformer to the utility power
14. Size of the pump room
15. Size of the electrical room
16. Transformer pad
17. Size of the emergency generator
18. Size of the diesel storage tank
19. Size of the transfer switch
20. HVAC system sizing
21. Overhead crane size

Flattening the system head curve, in addition to saving on equipment costs, also results in a much easier design and corresponding energy efficiency. A flat system head curve provides a system with only one design point, which can result in continuous operation at the best efficiency point. Also, a flat system head curve can result in a system design without the use of VFDs, resulting in a gain in electrical efficiency. Figure 10 shows the difference between a system with high friction head loss and a system with a flat system head (curve).

Conclusions

An overall understanding of the pumping system can lead to an integrated approach to energy efficiency that can be combined to yield significant reductions in energy use. Figure 11 is a summary of the approach to evaluating an existing pump station.

Figure 12 shows the approach to evaluating improvements to an existing pump station after a utility has done the preliminary evaluation.

Similar means and methods can be used to design a new pump station. Figure 13 shows that approach.