The Fast and the Curious: Investigating the Energy Savings from Adjustable Speed Drives beyond Load Matching

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ABSTRACT

Power Drive Systems (PDS) are fast becoming commonplace due to the dramatic energy saving potential of reducing motor speed at times of reduced demand. A PDS is the combination of an electric motor, variable speed controls, and sensors to provide feedback to on equipment operation. While the market is adopting PDS technology, the benefits of constant load applications have not been adequately documented to justify installation of variable speed technology in a constant load application. This lack of data has led installers, purchasers, and energy efficiency auditors to overlook the benefit PDS can have on constant load systems, undercutting the energy savings potential from this technology. This paper uses operational data to characterize the difference in savings potential from installing a PDS on a pump serving a constant load compared to a pump serving a variable load. With more than 25 percent of commercial energy consumed by motor driven products, specifically pumps, fans, and compressors, this paper also investigates the applicability of the pump findings to these other end uses.

Introduction

Electric motors paired with variable speed controls and sensors providing operational feedback, or "Power Drive Systems" (PDS), offer significant energy savings potential in commercial applications (DOE 2013). However, while adoption of PDS has increased steadily since the mid-20th century, several barriers remain that prevent their ubiquitous adoption (Jahns and Owen 2001). While initial cost remains the primary barrier, there is a perception that only variable load systems, or systems where the needed flow fluctuates across the equipment's operating range, can provide additional energy savings potential of PDS. Consequently, many believe a PDS will not justify its cost unless it is installed on highly variable loads, a view that has limited the adoption of PDS technology and its potential energy savings (DOE 2002). This viewpoint fails to account for the ability of a PDS to use speed control to match the needed power of a constant load system ("right-size" a piece of equipment), as well as the numerous non-energy benefits associated with PDS.

If equipment purchasers and energy efficiency program designers accounted for the potential benefit from right-sizing would that tilt the scales towards greater PDS adoption? This paper seeks to address that question by leveraging recently compiled data on pump operation in the Pacific Northwest to quantify the energy savings associated with PDS in a range of variable and constant load pumping applications, as well as apply those findings to estimate the energy savings potential from installing a PDS across a variety of typical commercial building loads.

Background

The development of variable speed drives, which enable motor speed changes during equipment operation, without discrete intervals, constituted a breakthrough for motor technology (Jahns and Owen 2001). As opposed to a motor operating at a single point and mechanically intervening to control system impact (e.g., installing gear sets on a motor or throttling pump flow), variable speed drives allow motors to directly and dynamically meet the requirements of the load. This advancement not only makes the motor and control system smaller and easier to apply, but it also decreases the losses associated with mechanically controlling a load (Aloor 2011). These increases in efficiency, when applied to the 25 percent of primary energy consumed by electric motors, represent major decreases in energy consumption worldwide (DOE 2013).

Multiple different types of electronic, continuously adjustable speed drives have been developed, with the most common being variable speed drives (VSD) and variable frequency drives (VFDs). A VSD is an electric device that changes the speed of a motor by varying the supplied voltage. VSDs can operate on both alternating- and direct-current motors (ABB 2011). In contrast, VFDs operate by changing the frequency of the electricity supplied to a motor and only apply to alternating-current motors (Eaton 2013). Any type of motor control also requires sensors and control logic to determine the requirements of the systems and respond accordingly. The term "Power Drive System" (PDS) refers to the combination of an electric drive, the motor, and the sensors on the system (GAMBICA/REMA 2012). A PDS and the driven equipment to which it is applied (e.g., fan, pump, etc.) represents an extended motor product. Figure 1 illustrates this relationship.

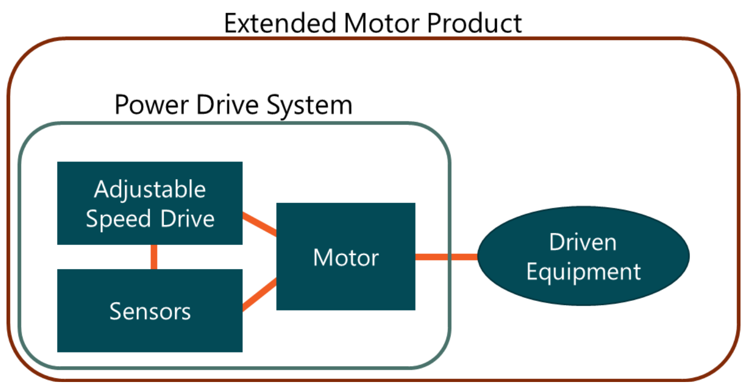

Figure 1. Relationship between a Power Drive System and an Extended Motor Product. *Source: Gambica/Rema, 2012*

The energy savings potential of a PDS is dependent on the application of the motor. The motor industry classifies motor applications into three different categories: Variable Torque, Constant Torque, and Constant Horsepower (NEMA 2015). Each of these applications represents a different relationship between power and speed. This relationship is indicative of the utility of the motor and the relationship between power and speed is indicative of the potential for energy savings.

Variable torque applications, such as pumps, fans, and certain compressors, follow the affinity laws, a set of physical principles that govern fluid flow (Geankoplis 2003). The affinity laws dictate that power is proportional to the cube of an impeller's rotational speed. This cubic relationship between speed and power translates to large energy savings potential in systems where the motor speed can be reduced. As such, variable torque applications, which are typical in commercial building applications, are considered the best candidates for PDS installation (a 50% reduction in motor speed results in an 87.5% reduction in energy consumption).

Constant torque applications serve loads where the torque does not change as the speed of the motor changes, but power changes linearly with speed. Constant torque applications are commonly seen in systems that mechanically move material, like conveyor belts, positive displacement pumps, and reciprocating/rotary compressors (Schneider S.A. 1995). The energy savings in constant torque applications are often less than those seen in variable torque applications since they do not benefit from a cubic relationship between motor speed and motor power.

Constant horsepower applications differ from variable and constant torque applications in that speed and torque are inversely proportional to each other. In constant horsepower applications the torque on the motor decreases as the speed increases, while power remains constant. Constant horsepower applications include winding machines (e.g., wire winding or paper-drum loading) and milling machines (NEMA 2015). PDS installed in these applications do not achieve energy savings from decreasing the speed of the motor.

Variable torque applications are the most common motor driven systems in the commercial sector and are the focus of the remainder of this paper. Constant torque and constant horsepower applications more commonly serve material handling and processing loads in industrial applications. These applications are less likely to see the large energy savings of variable torque applications, but PDS adoption is often driven by the improved control and decreased maintenance PDS can provide (de Almeida, Ferreira and Both 2005).

Analysis

Energy savings are the most common justification for the installation of a PDS (Tamez 2019). For a pump system that requires flow below the design point[1], a PDS offers energy saving when compared to the two most common methods of flow control: restricting system flow—or "throttling the system"—by increasing the discharge pressure to decrease flow through the system and recirculating flow away from the process and back through the driven equipment—or "system bypass" (DOE 2006). These methods achieve flow control but do not significantly decrease the energy consumption of the system. In contrast, a PDS decreases the speed of the motor to decrease the flow, attended by a cubic decrease in power consumption.

These mechanisms will produce energy savings in both variable load and constant load systems. However, while it is generally accepted that the energy savings of a system that operates at multiple load points can justify the purchase of a PDS by matching the load of the system, the potential for cost-effective energy savings on systems that spend the majority of their time at a single duty point has not been well documented. Two reasons are often presented against using PDS for right-sizing a pump:

1. PDS add a transition between power delivery and the motor, which inherently adds losses to the motor system and decreases overall system efficiency.

[1] Design Point in a system represents the maximum flow and pressure that an extended motor product is expected to produce in a given application. Design engineers use these values when designing a system and determining which equipment will be installed.

2. Installers can trim (decrease in diameter) pump or fan impellers or use other mechanical means to meet specific operating points. This is less expensive than purchasing and installing a VSD and achieves the same end goal.

These reasons for not utilizing a PDS for right-sizing do not always hold weight. In the European commission's study of the EU's Ecodesign requirements for water pumps the EU analyzed the difference in overall system efficiency when a specific duty point is reached via speed control, which increases motor/drive losses, versus trimming the impeller, which decreases hydraulic efficiency. Over the majority of the operating range, the extended motor product efficiency was not impacted by the presence of a VSD. When the duty point was met via speed control the system saw an average increase in hydraulic efficiency of 4% compared to trimming the impeller (European Commission 2018). The study found that this increase in hydraulic efficiency compensated up for the losses due to the presence of a drive, which are commonly estimated at 3% (NREL 2014). While this example looks at a single pump, it shows that a blanket statement of "the addition of a drive decreases system efficiency" is not always correct.

The second justification for not right-sizing with a VSD, the fact that an impeller can be trimmed, does not account for the underlying reasons a pump is oversized to start with. The solution of trimming an impeller assumes pumps are oversized solely because motors and pumps are sold at discrete size intervals, and a static operating point achieved through a smaller impeller effectively serve the needs of the system and the system designer. While the availability of different pump/motor sizes is a factor in motor oversizing on pumps, this is not the only cause of oversizing. Often design engineers will intentionally oversize motor driven equipment to ensure any errors or uncertainty in system design and construction do not result in the installation of a motor driven product that cannot meet the installed or future load of a system (DOE 2015). Trimming an impeller at equipment selection will not account for this oversizing, because while the pump is correctly sized for the specified duty point, it is the duty point itself that is conservatively overstated. Impellers can also be removed and trimmed in the field to respond to actual, installed design conditions; however, this is an expensive process that is not often pursued. Therefore, trimming impellers are not a comprehensive or energy efficient solution to ensuring optimum pump operation at as-installed field conditions.

While the discussion above shows that drive losses and trimming an impeller, the two most common arguments against installing a PDS on a constant load system, are not as applicable to actual pump installations as most think, they do not address the magnitude of energy savings and cost effectiveness associated with right-sizing a motor driven product using a PDS. To investigate the energy savings potential, this analysis leverages a subset of the data the Northwest Energy Efficiency Alliance (NEEA) collected to characterize pump operation in the Pacific Northwest (NEEA 2019). NEEA collected data on over 400 pumps to assess the operating and installation characteristics of pumps. Of the data collected, 132 clean water pumps had enough audit and operational data to develop load profiles and estimate the pump performance curve. Based on the NEEA dataset, each pump is classified based on its operational characteristics into one of the following two categories:

1. Constant load, where the pump spends 90% or more of its time at one operating point, or
2. Variable load, where the pump spends more than 10% of its time at two or more operating points.

This classification is made regardless of the presence or absence of variable speed control capabilities. By classifying the systems as either variable or constant load based on pump operation rather than the presence of a drive, the research team was able to investigate the differences in energy savings between right-sizing and load matching, as well as the penetration of PDS in different types of applications.

Pump Energy Savings

This section characterizes the difference in energy savings between constant and variable load systems, within each pumping application. The energy savings in each case are calculated by comparing the theoretical energy performance of each pump under two different control methods: throttling the system (i.e., constant speed flow control) and changing the speed of the pump (i.e., variable speed flow control). The data used in the analysis include commercial HVAC pumping (cooling tower pumps, cooling loop pumps, heating loop pumps), commercial DHW pumping (pressure boosting pumps), industrial pumping, and municipal pumping. The results presented in this paper are limited to commercial pumping applications

Constant Speed Flow Control Energy Consumption Calculation

Certain physical properties govern the operation of pumps. At a constant speed, these physical properties dictate that a pump will operate with a defined relationship between the flow and pressure in the system. The performance curve of a pump (or "pump curve") represents this relationship. Practitioners use this relationship to control the flow rate of water through a system by increasing system pressure through "throttling," which can be done once, during system balancing, or over time, varying the flow rate in response to changing demand. This effect is shown in Figure 2, where throttling the system would move the pump from System Curve C to System Curve B on the pump performance curve. In this diagram, System Curve C represents the system curve at the "native" full speed operating point when the pump is initially installed. System Curve B represents the system curve when a system is throttled to meet a specific flow at full speed. The difference in pressure between where System Curve C and System Curve A intersect the Performance Curve represents the pressure added to the system by throttling.

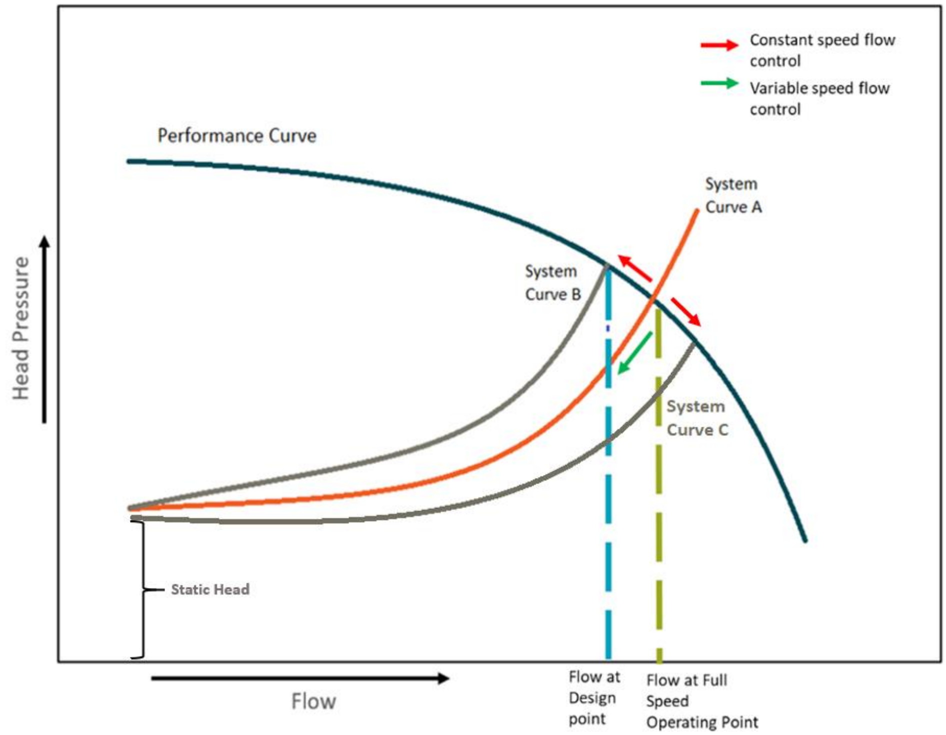

Figure 2: Pump performance curve and system curves, example showing the impact of throttling on the system curve vs decreasing speed.

This control approach is effective in decreasing flow, but results in higher operating pressures in the system and higher than necessary energy use. Using the load profile and performance curve for each pump, the team calculated the annual energy consumption of a pump with constant speed control, assuming the pump remains on the performance curve. Specifically, the team calculated the pressure and flow at each load point to determine the power draw based on those two variables. The average power draw of all load points, weighted by the percent of time a pump spent at each load point, represents the power draw of the pump operating with constant speed control.

Variable Speed Flow Control Energy Consumption Calculation

With a static, known performance curve, a characteristic of constant speed pump operation, the analysis can confidently calculate the power draw at each load point using the method discussed above. In contrast, when a pump operates with variable speed control there are more factors that impact the relationship between flow and pressure.

The performance curve, shown in Figure 2, is specific to a pump operating at a single speed. For pumps with variable speed control, pumping systems typically achieve the necessary flow by reducing the speed of the motor (which in turn reduces the speed of the pump), as opposed to increasing pressure in the system as in the constant load control case. As the speed of a pump is changed, instead of the flow and pressure moving along the performance curve, the relationship of flow and pressure is represented by the system curve, shown in Figure 2. The system curve for each application is unique and is based on two parameters: (1) the static head in the system[2] and (2) the operating point at full speed (i.e. where the system curve and the pump curve intersect at full speed).

Modeling the energy consumption of a pump using variable speed control requires information about the system curve for each pump. Predicting a pump's system curve requires information about the static head and full speed operating point, as well as the design point in the system. The team determined the system static head and full speed operating point values for each pump based on a combination of operational data and engineering judgement. Specifically, the static head is assumed to be zero for closed loop systems, which are largely unaffected by static head because they are circuits in which with suction pressure is equivalent to discharge pressure. For open loop systems, the static head used the values measured in NEEA's Extended Motor Products (XMP) research, shown in Table 1.

Table 1: Static Head Assumptions for Variable Speed Energy Consumption

NEEA XMP research application	Static head (% of head at Best Efficiency Point, BEP)
Commercial Cooling Tower	35%
Commercial Pressure Boost	35%
Industrial	22%
Municipal	22%

The operating point at full speed represents the intersection between the system curve and the performance curve with no incremental or artificial head created by balancing values. This is represented by where System Curve A, in Figure 2, intersects the full speed performance curve. Unfortunately, information on the non-throttled, full speed operating point and how that point relates to the required system design point is not available in most operational data sets, including NEEA's Pump Performance Database, since the collected operational data will always represent system performance after balancing (which is when throttling most often occurs), shown as System Curve B in Figure2.

For the full speed operating point, which is often at a higher flow rate than the design operating point, the team inferred the head and flow conditions based on the amount of information available for each pump:

- For pumps in NEEA's dataset equipped with variable speed drives and for which operational speed data exist, the team calculated the full speed operating point by applying the affinity laws to the measured data and scaling the head and flow rate up to full speed[3].
- For pumps in NEEA's dataset equipped with variable speed drives where operational speed data is not available, the team assigned the full speed operating point as the maximum flow rate observed in the data. This implies that there is no throttling in the system and that only the drive is used to control the pump flow rate by changing speed.
- For pumps that are not equipped with drives (i.e., constant speed pumps), whether on constant load or variable load systems, the team relied on analysis from the Department

[2] The static head is the pressure inherent to a system, or the pressure that a pump must overcome to start the movement of water. This value is dependent on the vertical difference between the inlet level and the discharge level of the liquid in the system. Static head is shown in Figure 2.

[3] In all cases where operational speed data exists the maximum speed of the motor is known.

of Energy (DOE) to inform the relationship between the design point and the full speed operating point. When DOE developed its analysis of pump operation to develop energy conservation standards, it established a range of typical full speed operating points based on BEP. DOE states that manufacturers and installers typically size pumps to operate within 75% to 110% of their BEP flow (DOE 2015). This paper uses the average of DOE's range of full speed operating points (92.5% of BEP flow) as the typical full speed operating point for constant speed pumps. The team applied this typical full speed operating point to the majority of constant load pumps in the analysis (20 out of 33), whose observed operating flow rates fall below the pump BEP. However, if the maximum observed flow rate was above 92.5% of BEP flow for a given pump, the analysis used that observed maximum flow rate directly as the full-speed operating point. Similar to variable speed pumps without speed data discussed above, this implies that the system is unthrottled and there was limited or no oversizing present in the system. This latter assumption applies to 13 out of 33 constant load pumps and, again reflects a conservative assumption as no "right-sizing" energy savings are available from these pumps.

Finally, to calculate the savings associated with variable speed control, one must determine the desired duty point for the pump. The team used the maximum flow rate observed in the data as the design point for the system, which represents a best-case scenario for the system, as experience suggests that some pumps are providing more head and flow than necessary and better balancing through variable speed control could achieve additional energy savings.

Energy Savings

The difference between the weighted average power draw for the different flow control methods (constant speed versus variable speed) represent the energy savings from the addition of a PDS. The average percent power savings for variable load systems is approximately double that of constant load systems, as shown in Table 2, although both constant and variable load systems demonstrate meaningful energy savings opportunities.

Table 2: Energy Savings by Load Type, Commercial Pumping Applications

Load Type	Average of Power Difference Normalized (kW/HP)	Percent Energy Savings
Constant	0.110	22%
Variable	0.243	43%

The magnitude of the savings in both cases varies considerably depending on the application. Figure 3 explores the energy savings from constant and variable load systems for the four commercial pumping applications present in the data.

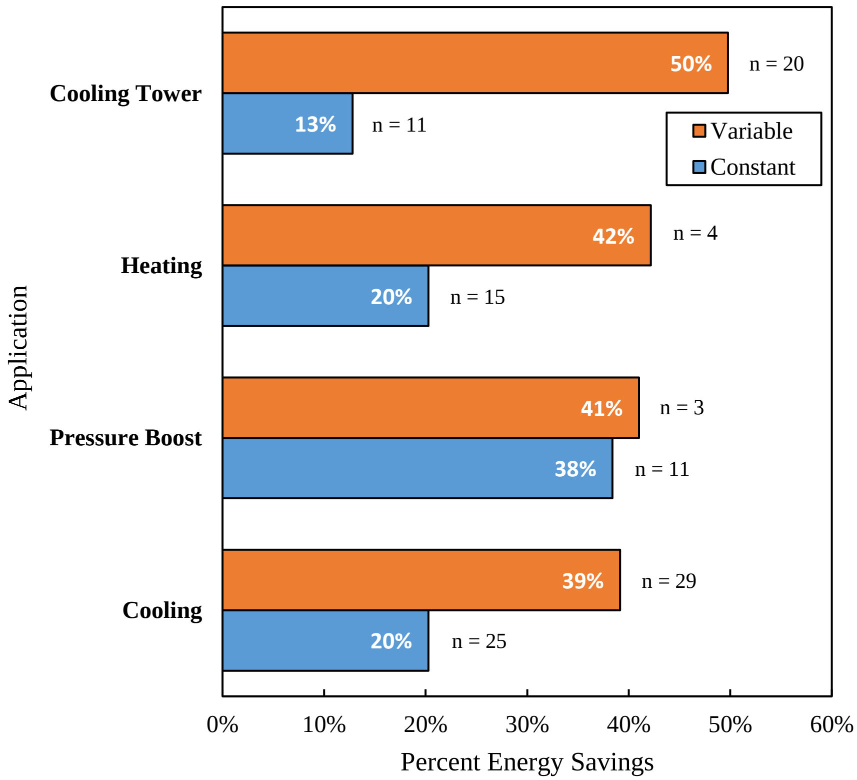

Figure 3: Percent energy savings, by application and speed control

While the energy savings potential in each application is larger for variable load pumps than constant load pumps, there are no applications that see no energy savings from PDS installation on constant load pumps. Cooling towers represent the biggest difference in savings potential between constant load and variable load systems. This difference could be driven by a tendency to install pumps in parallel and control one pump to manage the base load (no fluctuation on load) and use the other to meet any variability in demand. This would isolate the need for load-matching to one pump and allow the constant speed pump to operate at a more efficient duty point. Pressure boosting systems have the smallest difference between variable load and constant load savings, which again may be a result of applications specific control methods. Several pump manufacturers have developed new variable speed pressure boost skids that operate multiple PDS-equipped pumps dynamically (i.e., in parallel and at different load points for each pump), based on what is most efficient for the system to meet the design flow rate. Manufacturers estimate that the savings from such systems are up to 40% over traditional constant-variable speed pump skids (Ross 2019).

Specific research into patterns in system control by application is needed to identify the specific causes for these differences by application. However, even without more insight, this data shows that a PDS will produce significant energy savings when used for right-sizing on commercial pumping applications[4]. When considered against the incremental cost of a drive,

[4] Similar results were seen in the pumps analyzed from the industrial sector. There were no right-sizing energy savings observed for municipal pumps.

these energy savings are also very cost effective. As an example, for the constant load commercial HVAC Pumps average energy savings were 349 kWh/year/HP, or $41.86/year/HP at $0.12/kWh. With the average Commercial HVAC Pump being 20 HP (DOE 2015), the normalized cost of a VFD is approximately $35/HP (ATO 2019), a VFD installed on a constant load commercial HVAC system would have a simple payback of approximately 10 months.

Sensitivity Analysis

The energy savings calculated in the analysis make a strong case for installing PDS on both constant load and variable load systems. However, the amount of energy savings available through reducing the speed of a pump is highly dependent on the pump system curve in a given application, which is in turn depending on the static head and full speed operating point assumptions made in this analysis. To quantify the dependence of the savings on these two key variables, the team performed a sensitivity analysis to quantify the impact each has on the energy savings estimate.

For the sensitivity analysis on the static head assumption, the team established a range centered on the static head observed in NEEA’s XMP Research, with the lower bound being 50% less and the upper bound being 50% more than the average values, shown in Table 3.

Table 3: Static Head Values used in Sensitivity Analysis, shown in % of Head at BEP

Application	Low Bound	Used in Analysis	High Bound
Open Loop Commercial HVAC	17.5% of Head at BEP	35% of Head at BEP	52.5% of Head at BEP
Closed Loop Commercial HVAC	Held constant at zero (as discussed previously, in close looped systems suction pressure is equivalent to discharge pressure)		

Similarly, to assess the impact fluctuations in full speed operating point have on the energy savings, the team again established a range of values. Table 4 presents the ranges established for full speed operating point, which are developed based on the range of possibilities established in DOE’s pump analysis based around BEP.

Table 4: Full Speed Operating Point Assumptions for Default Analysis Case and Sensitivity Scenarios

<table>
<tr><th rowspan="2">Pump Case</th><th colspan="3">Full Speed Operating Point Assumption</th></tr>
<tr><th>Default Analysis Case</th><th>High-Savings Scenario</th><th>Low-Savings Scenario</th></tr>
<tr><td>Variable Speed Pumps with Speed Data</td><td>Head and Flow associated with next highest nominal speed case</td><td rowspan="2">Head and Flow associated with 10% increase in flow on full speed pump curve</td><td>No change</td></tr>
<tr><td>Variable Speed Pumps without Speed Data</td><td></td><td></td></tr>
</table>

Constant Speed Pumps with Maximum Flow Above 92.5% of BEP	Head and Flow associated with maximum observed flow rate (i.e., design point)	Head and Flow associated with flow rate 10% greater than maximum observed flow rate	Head and Flow associated with maximum observed flow rate (i.e. design point)
Constant Speed Pumps with Maximum Flow Below or equal to 92.5% of BEP	Flow at 92.5% of BEP and Head on the full speed pump curve	Flow at 102% of BEP flow and Head on the full speed pump curve	Flow at 70% of BEP flow and Head on the full speed pump curve

Table 5 shows the impact variations in static head and full speed operating point have on the energy savings.[5] The energy savings range from 23% to 31% in constant load systems and 40% to 55% in variable load systems as a result of variations in static head. Variable load systems see a broader range of savings. This is not unexpected, as variable load systems spend time at multiple points further down the system curve which is where static head has the largest impact on energy consumption. Variations in full load operating point has almost no impact in energy savings for constant load systems, as shown in Table 6. For variable load systems, the energy savings fall, on average, between 40% to 45%, with heating having the broadest range at 36%-47%.

Table 5: Percent energy savings calculated with static head range applied, by load type

Applications	Percent Energy Savings			
	Constant Load		Variable Load	
	Low Limit, Static Head	High Limit, Static Head	Low Limit, Static Head	High Limit, Static Head
Cooling Tower	11%	15%	41%	58%
Pressure Boost	31%	46%	33%	49%

Table 6: Percent energy savings calculated with a full speed operating point range applied, by load type

Applications	Percent Energy Savings			
	Constant Load		Variable Load	
	Low Limit	High Limit	Low Limit	High Limit
Cooling	20%	20%	37%	40%
Cooling Tower	12%	13%	44%	53%
Heating	20%	21%	36%	47%
Pressure Boost	37%	39%	40%	42%
Average	22%	23%	40%	45%

[5] The analysis assumes no static head in closed loop systems, so Table 5 does not include commercial chilled water and commercial heating

The variability of the energy savings here, again, is driven by where on the system curve the pump is spending most of its time. Lower flow rates have less of a difference between the head pressures of the different system curves than higher flow rates. This means pumps that spend more of their operating time at lower flow rates will have less variability due to changing the full speed operating point.

The sensitivity analysis results—an average difference in energy savings of 15% from the range of static head and 5% from full speed operating point—do not change the overall results of the analysis. Even in the low energy savings case, we see significant potential for energy savings in both constant load and variable load systems. However, the analysis and results presented here are based on multiple assumptions surrounding the actual operating point and *ideal* operating point, accounting for pump sizing and system static head considerations. As such, the findings are therefore representative and indicative, however this uncertainty makes calculating the exact energy savings and payback periods from installing drives in constant and variable load applications difficult. Future research into pump system design and sizing would significantly help characterize this uncertainty.

Expanding the Analysis to Other Commercial Motor Applications

While pumps represent a significant energy savings opportunity in commercial buildings, other commercial motor-driven loads, such as, fans and compressors are also important to consider. Across motor driven applications, users widely recognize that there are energy savings and operability benefits associated with applying PDS on variable load applications and this is just as true for fans and compressors (DOE 2002). However, when considering the benefit of PDS in constant load systems, we must consider the current control and commissioning methods employed in these applications and how these compare to variable speed control. The analysis showed that energy savings available from right-sizing in pumps is cost justifiable in most commercial applications due to 1) the tendency for pumps to be oversized and 2) the control method used to meet the system's duty point (throttling a pump system) is dramatically less efficient than speed control. Therefore, to understand the applicability of the pump's savings analysis to fans and compressors, we need to consider these two factors for both fans and compressors.

Fans are variable torque applications and are adherent to the affinity laws discussed above. This means that fans have a similar, cubic relationship between power and speed as pumps, showing a similar potential for energy savings. However, beyond the physical properties of a system, flow through fans is controlled differently than with pumps, which impacts the energy savings potential from right-sizing with a PDS. There are several methods for airflow control in constant speed fan systems: outlet dampers (or vanes), inlet dampers (or vanes), disc throttle, and variable pitch blades. Fans are also sometimes controlled with mechanical sheaves or belts that reduce the fan speed to achieve a given flow rate. This achieves the same affinity law benefits as a PDS, but may incur additional transmission losses and is not dynamic or as precise in dialing in the specific airflow needed by the application at any given time (DOE 2003).

In general, these methods are all more efficient then throttling a pump, since they reduce torque on the system and thereby the power required by the system is decreased, however the decrease is not as large as with controlling speed via PDS, especially at very low flow rates. Right-sizing with a PDS will have the largest impact on fans that are currently controlled by outlet vanes and disc throttles, whereas the benefit to a PDS over inlet vanes is seen at lower flow points and would most likely not be realized in a right-sizing application (DOE 2003). From an energy perspective, a PDS does not present an increase in efficiency over variable pitch blades or belts and sheaves, however the improved controllability and visibility into system performance provided by a drive may provide significant additional benefits beyond energy savings.

For compressors, over 95% of compressors sold are positive displacement compressors, which are considered constant torque motor applications. This means power is proportional to speed, which equates to less energy savings for decreasing motor speed. Compressors that are not equipped with PDS usually employ either an on/off style of control or one of two more dynamic control methods: inlet valve modulation or variable displacement. In the latter two control methods, the system air requirements that the compressor must meet are reduced, which results in lower power requirements (DOE 2016).

Similar to fans, compressors also can reduce energy consumption by using PDS compared to conventional control methods, however potentially not as much as pumps due to the more efficient control options available (including inlet valve modulation and variable displacement) (DOE 2016). However, these energy savings need to be considered alongside the potential to better control system pressure in both constant load applications.

In summary, the energy benefits for PDS in fan and compressor applications is likely smaller than for pumps, since the existing control methods already serve to reduce the load somewhat at reduced flow rates, especially in constant-load applications. However, the non-energy benefits may be important to consider and still lead to cost-effective application of PDS in a majority of fan systems, even for constant speed fans where users can precisely dial in and adjust the flow rate and monitor equipment performance overtime with a PDS. More research is needed, especially on the sizing and commissioning practices employed in these systems, to fully assess the potential of PDS in fan and compressor systems on both constant load and variable load applications.

Non-Energy Benefits

PDS also produce benefits that are less easily quantifiable than the energy savings presented in this paper. These benefits include:

- **Decreased maintenance** through reduced equipment wear when starting and operating motors and motor-driven equipment,
- **Process improvements and improved control**, which can have meaningful impacts on overall system efficiency (e.g., ensuring appropriate return water temperatures to a condensing boiler) or better respond to changes in system load due to unexpected increases or decreases in demand, and
- **System connectivity and visibility**, which allow operators to better maintain efficient equipment and system performance (i.e., fault detection) (Tamez 2019).

The identification of these benefits is a process unique to each system because these benefits are inherent to the operation of the extended motor product (e.g., a conveyor system will see similar non-energy benefits to other conveyor systems, but different benefits than escalators). When considering equipment payback, energy savings are often prioritized over non-energy benefits, but for many applications even minimal energy savings from PDS could be economically justified if the NEB’s are accounted for.

Conclusions and Next Steps

While it is commonly accepted that Power Drive Systems can save significant energy in certain applications, the paper shows that PDS are more broadly applicable—and cost effective—to a range of systems and application types. This underappreciated fact, coupled with the inability to monetarily quantify the non-energy benefits made possible by PDS, represent key barriers to greater PDS adoption.

In this analysis, there were significant and cost-effective energy savings associated with both right-sizing a pump with a PDS in constant load systems as well as load matching in variable load systems, as summarized in Table 7. Notably, savings from installing a PDS in constant load systems were associated with an average 22% and a payback of ten months. This implies that a PDS will most likely produce energy savings in any application, regardless of the load.

Table 7: Summary of Energy Savings and Payback Period for Constant Load and Variable Load Systems

System Type	Savings	Payback Period
Constant Load Systems	22%	10 months
Variable Load Systems	43%	4 months

This finding, however, depends on the sizing and characteristics of the load. The sensitivity analysis highlighted the impact of the team's assumptions on the energy savings results. Using the little information known about trends in system static head and full speed operating point, the range of energy savings produced uncertainty between 5 and 15%, but did not affect the overall conclusion that PDS have the potential to save energy in a variety of systems, regardless of the inherent "dynamics" of the system load. However, this uncertainty underscores the need to further research into pump sizing and balancing methods to better characterize the energy savings potential from using PDS to optimally balance constant load systems. This future research, which could incorporate both field measurements of actual systems and interviews with TAB Contractors, would help fill a gap that exists in the body of information on pump operation, and further corroborate the suitability of PDS in all load applications. In addition, more work is needed to extrapolate these findings to other equipment types. While we believe the findings from the pumps analysis are representative of other variable torque applications, more detailed review of fan and compressors systems and load profiles could confirm this finding. Further review of the energy savings potential of constant torque and constant horsepower applications is also needed. However, the typically more industrial and process-focused constant torque and constant horsepower applications stand to benefit significantly from several of the non-energy benefits presented in the paper, which may outweigh the energy saving benefits and cost justify investment in a PDS on those grounds alone.

Non-energy benefits are harder savings to quantify, both in theory and practice. Both decreased maintenance and process improvements have the potential for large impacts on the total cost to operate a facility. These savings are difficult to generalize because they are different in each application and unique to each system. This inability to quickly demonstrate the monetary value of their non-energy benefits remains a headwind facing PDS adoption, despite manufacturers efforts to promote non-energy benefits. A standardized method or tool for quantifying PDS' non-energy benefits could enrich their value proposition. In contrast, the energy savings are smaller for constant torque and constant horsepower systems, making non-energy benefits a larger portion of the total system savings. The ability to easily and confidently calculate those savings could drive adoption of PDS in these applications as well.

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