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# Power Drive Systems: Energy Savings and Non-Energy Benefits in Constant & Variable Load Applications

PREPARED FOR:

Geoff Wickes, XMP Product Manager

*in collaboration with*

National Electrical Manufacturers Association (NEMA)

PREPARED BY

Cadeo Group

107 SE Washington Street, Suite 450

Portland, Oregon 97214

Northwest Energy Efficiency Alliance

PHONE

503-688-5400

EMAIL

info@neea.org

## Acknowledgements

The National Electrical Manufacturers Association (NEMA) represents nearly 325 electrical equipment and medical imaging manufacturers that make safe, reliable, and efficient products and systems. Its combined industries account for 370,000 American jobs in more than 6,100 facilities covering every state. These industries produce $124 billion in shipments and $42 billion in exports of electrical equipment and medical imaging technologies per year.

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# 1. Introduction

Electric motors—invaluable for their ability to convert electric energy into useful mechanical energy—now constitute one of the largest energy end-uses in the world, consuming 40 percent of electrical energy worldwide (IEA, 2011; US EIA, 2014). That figure would loom even larger if not for tremendous advances in motor technology over the past 50 years: motors once considered premium efficiency are now the standard, and low-cost electronics have enabled the application of energy-saving controls in increasingly smaller motors. One of the biggest improvements has been the development of adjustable speed technology, which is the ability to change the rotational speed of a motor without shutting the equipment down.

The use of adjustable speed drives on motor-driven systems— "Power Drive Systems" (PDS)—offers significant energy savings potential in commercial and industrial applications. While adoption of PDS has increased steadily since the mid-20th century, several barriers remain that prevent their ubiquitous adoption. A primary barrier is the perception that only variable load applications, such as heating and cooling systems responding to variable climate conditions, can realize the 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. This viewpoint, however, fails to consider other energy savings mechanisms and/or non-energy benefits that come from the installation of a PDS.

If these additional benefits were more fully understood and accounted for in system design and purchasing behavior, would that tilt the scales toward greater PDS adoption? That question is the subject of this paper. To address it, the authors conducted two primary research tasks. First, the research team leveraged recently compiled data on pump operation in the Pacific Northwest to quantify the energy savings associated with PDS in a range of inherently variable and inherently constant load applications. These data included operating characteristics for132 clean water pumps, including flow rate, system pressure, and power consumption. The team analyzed these data to answer four questions:

1) Are there pumping applications that are intrinsically constant, and, if so, does this invariability prevent PDS from being cost-effective?
2) Are the energy savings associated with such inherently constant load applications (i.e., through right-sizing) comparable to those from inherently variable load applications (i.e., through load matching)?
3) Are applications already taking advantage of PDS savings for both constant and variable load systems?
4) How can any energy savings findings identified in question 2 be applied to other applications?

Second, the team conducted a literature review to identify and characterize other benefits associated with PDS that might influence users to select a drive to control a system. These benefits, while not directly related to the efficiency of the motor system's operation, can often have a larger monetary impact than the energy savings. Properly understood (and marketed), these attendant PDS benefits could potentially drive greater PDS adoption.

# 2. Background

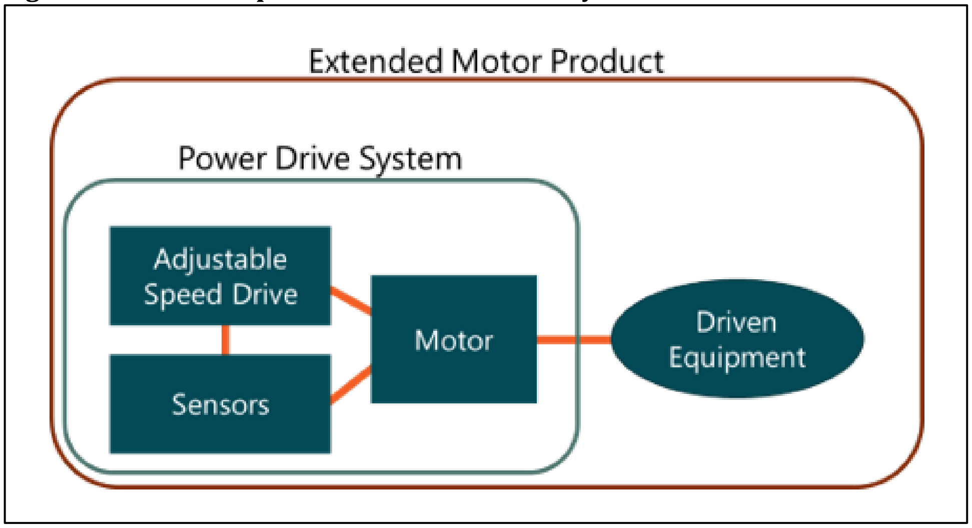
## 2.1. History and Developments

Since the advent of motor technology in the 1800s, many innovations have extended the applicability of electric motors and/or improved their efficiency. The development of motor output control, such as PDS, was one such advancement. The ability to adjust motor operation to meet a specific load allows manufacturers and installers to apply motors more efficiently to more applications. Historically, motors operated at a single speed dictated by the motor configuration and frequency of the supplied electricity. If a driven product needed a different operating speed, an operator installed mechanical devices to change the motor's impact on the driven load. This method allowed *the equipment* to operate at different speeds, but its operation was not continuous: because *the motor* could only operate at a single speed, operators had to shut systems down to change the speed. In addition, mechanical controls often featured discrete speed options, as opposed to the continuous speed variation afforded by PDSs.

The development of continuously variable speed drives, which enable motor speed changes during equipment operation without discrete intervals, constituted another breakthrough. As opposed to a motor operating at a single point and mechanically intervening to control system load, continuously variable speed drives allow motors to directly meet the requirements of the load. This advancement not only made the motor and control system smaller and easier to apply, but it also decreased the losses associated with mechanically controlling a load.

Today, the most efficient control methods employ electronic, continuously adjustable speed drives, often called variable speed drives (VSDs) or variable frequency drives (VFDs). While often used interchangeably, VFDs and VSDs do in fact differ. 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. In contrast, VFDs operate by changing the frequency of the electricity supplied to a motor and only apply to alternating-current motors. 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 (fan, pump, etc.) represents an extended motor product. Figure 1 illustrates this relationship. This white paper focuses on PDS and uses the term "adjustable speed drive," or ASD, to refer to the drive component of a PDS.

**Figure 1. Relationship between a Power Drive System and an Extended Motor Product**




While PDS can be used in many systems, the suitability of any given application depends on the type of system the motor serves. This section provides an overview of the different types of applications a motor can serve, and the relationship between the speed of the motor and the power draw needed to drive the system, a relationship that impacts the energy savings a PDS can provide.

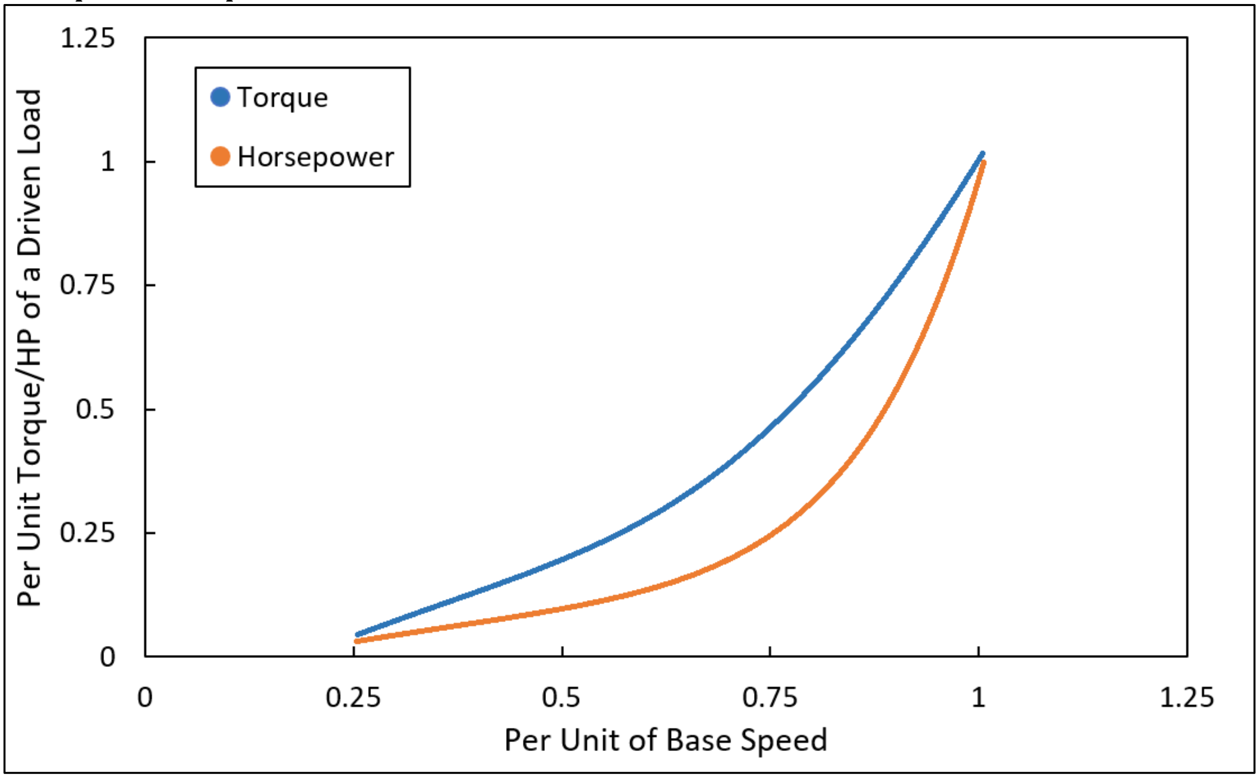
## 2.2. Applications

As discussed previously, the electric motor is ubiquitous and serves a wide range of systems, from fluid movement systems such as pumps, fans, and compressors (which are the focus of the energy savings analysis in this white paper) to industrial machinery such as presses and conveyor belts. The benefit of PDS installation in this variety of systems depends on the general application of the motor. The motor industry classifies motor applications into three categories: Variable Torque Applications, Constant Torque Applications, and Constant Horsepower Applications (NEMA, 2015).

### 2.2.1. Variable Torque Applications

Current practice often considers variable torque applications—those in which a decrease in motor speed results in a decrease in load torque—as the most suitable applications for PDS. This is because a change in motor speed represents a change in power proportional to the cube of the speed. For example, in variable torque applications, a 50% reduction in motor speed results in an 87.5% reduction in energy consumption. Figure 2 shows the relationship between torque, horsepower, and speed.

**Figure 2. Variable Torque Application: Relationship between Torque and Speed and between Horsepower and Speed**




Systems such as fans, pumps, and centrifugal compressors are all variable torque applications. These systems follow the affinity laws, a set of physical principles that govern fluid flow (Geankoplis, 2003). The affinity laws dictate that an impeller's rotational speed is directly proportional to the flow rate through the system; that pressure in a system is proportional to the square of the speed; and that power is proportional to the cube of the speed, shown in Equation 1.

$$\frac{Speed_1}{Speed_2} = \frac{Flow_1}{Flow_2} = \frac{Pressure_1^2}{Pressure_2^2} = \frac{Power_1^3}{Power_2^3} \tag{1}$$

For a system that requires flow below the design point,[1] a PDS offers energy savings benefits compared to the two most common methods of flow control. The first method typically employed is to restrict system flow—or "throttle the system"—by increasing the discharge pressure to decrease flow through the system, much like placing a thumb over a garden hose. The second method is to recirculate flow away from the process and back through the driven equipment (e.g., "system bypass"). 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 (following the laws in Equation 1), attended by a cubic decrease in power consumption.

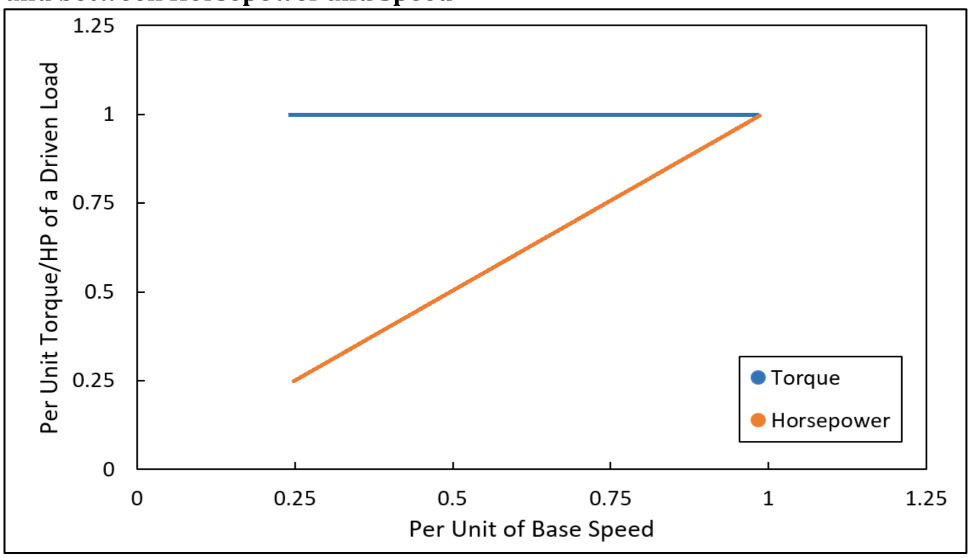
[1] Design point in a system represents the maximum flow and pressure that an extended motor product is expected to produce in a given application. Design engineers use these values when designing a system and determining which equipment will be installed.

The data analysis in Section 3 investigates the energy savings from the PDS installation. The analysis focuses on variable torque applications (specifically pumps). This white paper also investigates the applicability of pump energy savings to different variable torque applications.

### 2.2.2. Constant Torque Applications

In contrast to variable torque applications, constant torque applications serve loads where the torque does not change as the speed of the motor changes. Constant torque applications are commonly seen in systems that mechanically move material, such as conveyor belts, positive displacement pumps, and reciprocating compressors (Schneider S.A., 1995). In constant torque applications, the horsepower changes linearly with speed. Figure 3 shows the relationship between torque, power, and speed in a constant torque application.

**Figure 3. Constant Torque Application: Relationship between Torque and Speed and between Horsepower and Speed**

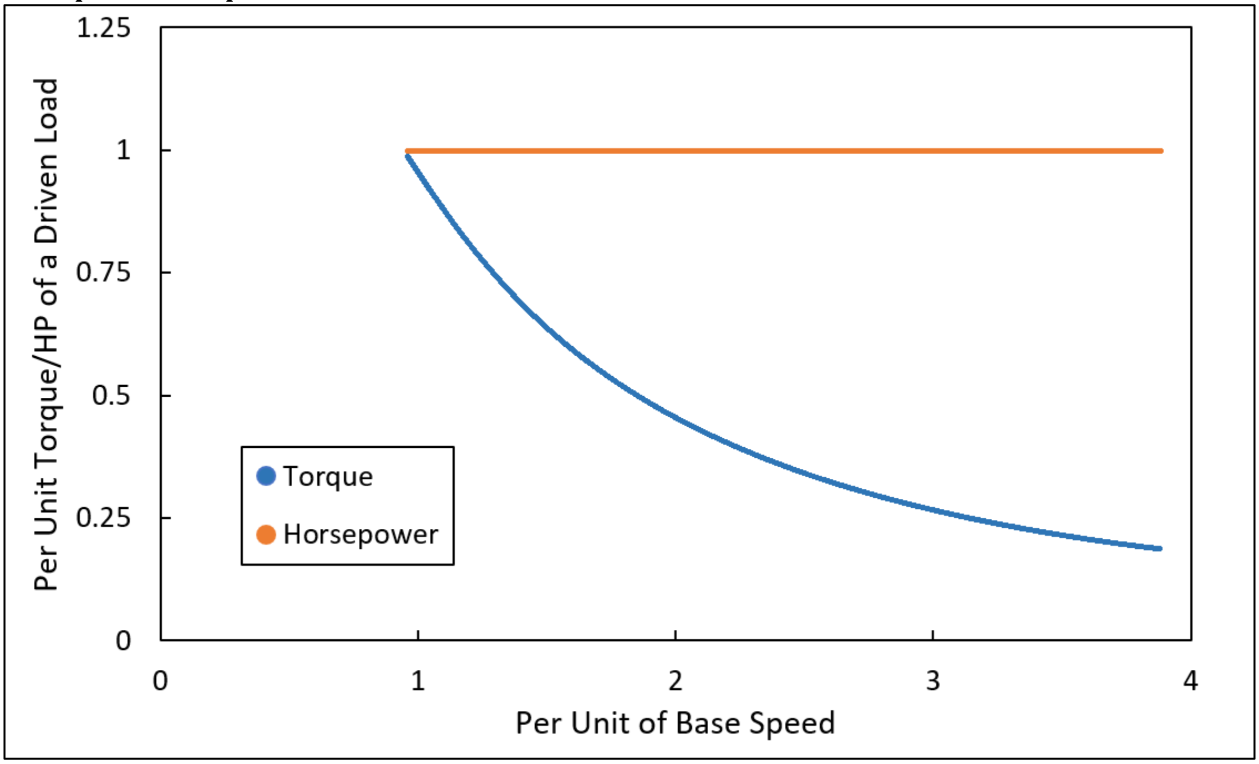



While installers use PDS in constant torque applications, the energy savings are often less than those seen in variable torque applications since these applications do not follow the affinity laws and do not benefit from a cubic relationship between motor speed and motor power. The savings from PDS installations on constant torque applications are often due to the ability to control the speed of the driven unit to impact material flow rate, which can have significant logistical and process-related benefits in addition to energy savings. For example, a PDS that increases or decreases the speed of a conveyor belt in a coal power plant to match the demand from the crusher would achieve energy savings relative to traditional methods. A non-PDS would traditionally turn on and off, operating for several hours at a time because the conveyor and crusher were oversized compared to the needed supply. In one such example, adding a PDS to a conveyor belt system generated 10% energy savings, but also yielded a 60% reduction in energy cost due to the ability to adjust operation timing to optimize for schedule-based pricing (Zhang & Mao, 2017).

### 2.2.3. Constant Horsepower Applications

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, maintaining a constant horsepower. Figure 4 presents the relationship between speed, torque, and horsepower in a constant horsepower application.

**Figure 4. Constant Horsepower Application: Relationship between Torque and Speed and between Horsepower and Speed**




Constant horsepower applications include winding machines (e.g., wire winding or paper-drum loading) and milling machines. PDS installed in these applications achieve lower energy savings relative to variable and constant torque applications. However, as with constant torque applications, the major benefits from a PDS on constant horsepower applications stem from changes to production process the PDS make possible. Those benefits can be substantial.

# 3. Energy Savings Analysis

Energy savings are the most common justification for the installation of a PDS. 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 energy savings on systems that spend the majority of their time at a single duty point has not been well documented. PDS add a transition between power delivery and the motor, which inherently adds losses to the motor system and decreases overall system efficiency, so it would seem logical that systems designed to spend the majority of the time at one duty point would not benefit from PDS and may even experience an increase in energy consumption. Perhaps counterintuitively, this theory does not play out in practice, where motors are often oversized and specified duty points (or design points) are often greater than the actual operating conditions experienced in the field (due to safety factors and rules of thumb implemented at the design stage).

This tendency to oversize motors results in the need to mechanically adjust systems to the actual system-required duty point, via either belts/gears or pressure regulation. In contrast, PDSs reduce motor speed to achieve the system-required duty point and do so at a lower energy input than the mechanically controlled system. The efficiencies seen by running a motor more slowly to match its load often not only outweigh the incremental efficiency losses from the PDS, but also result in the potential for significant energy savings—even in constant load systems. This energy savings mechanism allows the drive to "right-size" the selected extended motor product to the actual load encountered in the field.

This section leverages the data collected through the Northwest Energy Efficiency Alliance's (NEEA's) Extended Motor Products (XMP) Research[2] to compare the energy savings potential for constant and variable load systems (in this case, pumps) and to provide a comprehensive picture of energy benefits from PDS across applications.

## 3.1. NEEA's XMP Pump Research

In 2018 and 2019, NEEA conducted field research with the goal of characterizing pump operation in the Pacific Northwest. Over the course of the study NEEA collected audit and operational data on more than 400 clean water pumps and circulators. The audit data collected included pump and installation characteristics such as pump type, model number, horsepower, application, and drive method. The operational data included motor speed, flow through the pump, power draw of the motor, and head of the system. With this information, NEEA investigated features of the pumping systems that impact energy consumption (NEEA, 2019).

This white paper leverages a subset of the data NEEA collected to assess the potential energy savings associated with installing a PDS on different systems. The analysis team determined the load profile for 132 pumps using the operational data and information from the pump curve.[3] This load profile represents the percent of operating hours a pump spent at six different load points (shown below in Figure 5). Figure 5 shows the average load profile of the pumps collected through NEEA's research.

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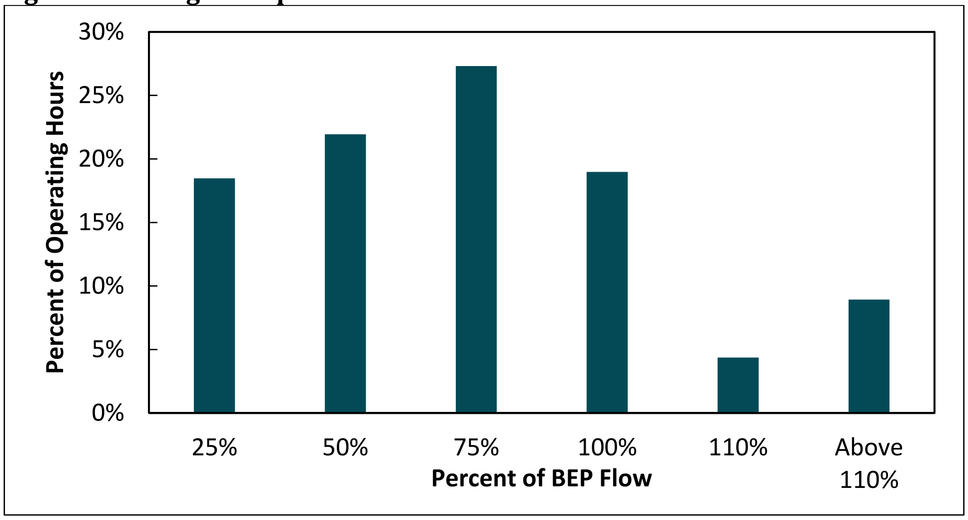
[2] NEEA's XMP Pump Research can be found at https://neea.org/img/documents/XMP-Savings-Validation-Research-on-Clean-Water-Pumps-and-Circulators.pdf

[3] Only 132 pumps had both the operational and audit data necessary to develop a full load profile.

**Figure 5. Average Pump Load Profile**




NEEA's research characterizes the load profiles and operation of the pump in terms of variation from Best Efficiency Point (BEP) as a consistent way to describe where the pump is operating on the pump curve and in relation to its most efficient operating region. However, a pump's BEP does not always (or often) equate to the design point or the full speed operating point of a pump when selected or installed in a given system. The design point of a given pump, as discussed previously, represents the *intended* maximum head and flow point that the pump is expected to produce in a given application. The design point is typically determined theoretically based on the equipment configuration and needs of the system and then used to select the appropriate pump for the application. Ideally, design engineers will select pumps with a BEP close to the system design point to minimize energy consumption. However, it is uncommon for the design point to be exactly consistent with the pump BEP; design engineers typically select pumps with the design point residing between 75% and 110% of BEP (DOE, 2015). Conversely, the full speed operating point refers to the flow and pressure the pump will *actually* produce when operating at full speed as installed with the system in an unthrottled state (i.e., all control valves open). The full speed operating point of a system can often be different than the design point used to select the pump due to safety factors and assumptions made during the design process that do not prove out in the field. For this white paper, the team typically assumed the pump's observed maximum flow was the full speed operating point of each system. The team then described this point, as well as the part load operating points, with respect to the pump's BEP to describe the portions of time each pump spent at each load point.

Using each pump's load profile, the team separated the pumps into constant and variable load systems. The team defined a constant load system as one that spent 90% or more of its time at one load point and a variable load system as one that spent more than 10% of its time at two or more load points. By classifying the systems as either variable or constant load based on pump operation rather than on the presence of a drive, the research team was able to investigate the following research questions:

1) Are there pumping applications that are intrinsically constant, and, if so, does this invariability prevent PDS from being cost-effective?
2) Are the energy savings associated with such inherently constant load applications (i.e., through right-sizing) comparable to those from inherently variable load applications (i.e., through load matching)?
3) Are applications already taking advantage of PDS savings for both constant and variable load systems?
4) How can any energy savings findings identified in question 2 be applied to other applications?

## 3.2. Are there pumping applications that are intrinsically constant, and does this invariability preclude certain applications from having viable payback for PDS?

The most often-cited benefit of PDSs is their ability to adjust the speed of the motor to match the needs of the motor-driven system. Common belief dictates that certain applications are not suitable for PDS because they intrinsically have a constant load profile. Using the load profile and the classification of variable versus constant load discussed in Section 3.1, the team investigated the distribution of pumps by load, within each application. Table 1 shows the number of pumps in each application, by load type. In this dataset, no pumping applications are composed exclusively of constant load pumps. Commercial heating pumps, pressure boost pumps, and industrial pumps all have higher proportions of constant load pumps than variable load pumps, but even in these applications at least 20% of the pumps are variable load.

**Table 1. Pump Loads, by Application**

| | Commercial HVAC | | | | | |
|---|---|---|---|---|---|---|
| Applications | Chilled Water Loop | Commercial Cooling Tower | Heating | Commercial Pressure Boost | Industrial | Municipal Water Treatment |
| **Constant Load** | 25 | 11 | 15 | 11 | 8 | 1 |
| **Variable Load** | 29 | 20 | 4 | 3 | 2 | 3 |

The difference in load type concentrations for the three non-commercial HVAC applications may be attributed to properties of the way pumps are operated. Manufacturers sell pressure boosting systems as a skid equipped with multiple pumps, with constant speed pumps paired with a pump that has a PDS attached that manages fluctuations in the load. This allows the control scheme to operate one pump at 100% BEP the entire time while the other pump turns on, off, or varies speed based on the demand for water. Municipal pumps operate in the same manner, with one pump serving the base load and a second pump managing any fluctuations in load. Industrial pumps serve such a broad range of applications within a facility that identifying the application as more constant load or variable load would be an oversimplification.

The difference between commercial chilled water loop pumps, cooling tower pumps, and heating pumps stood out to the team as a point to investigate further. While the analysis team considered that the difference in loading between heating pumps and the other commercial HVAC pumps may be an artifact of the data collection, of the 19 commercial heating pumps analyzed, approximately half had PDS and half did not. The ratio of constant load to variable load systems was also consistent between pumps with and without PDS. This consistency indicates that there is a factor intrinsic to the operation of commercial heating pumps that drives this difference. Research into the control logic of these systems would be necessary to determine the root cause of this difference.

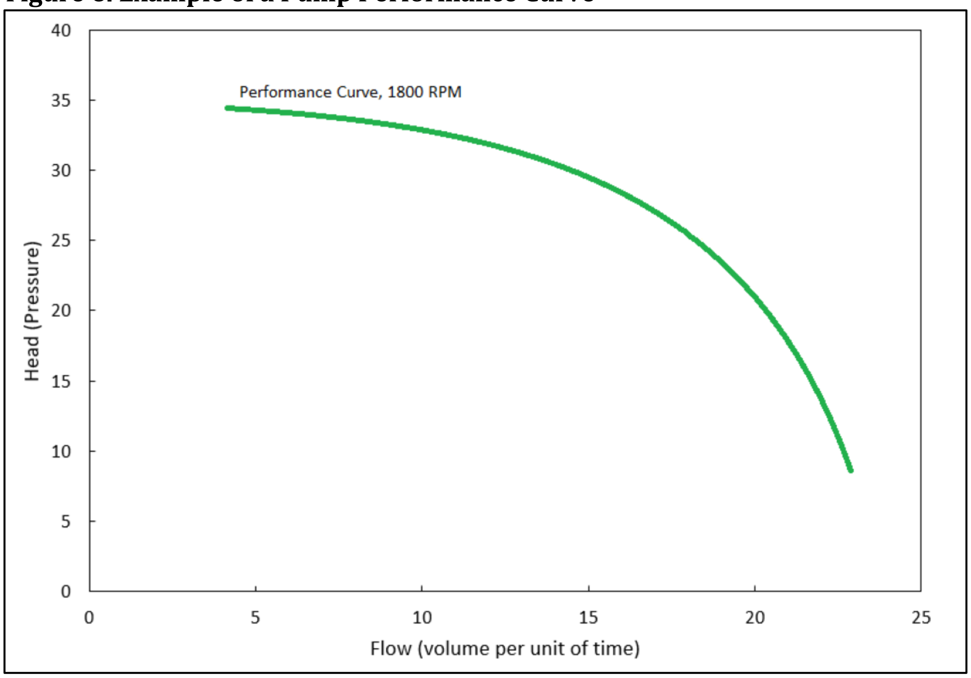
## 3.3. Are the energy savings associated with right-sizing comparable to load matching?

Section 3.2 investigated the inherent variability of pumping systems and determined that all applications include both variable and constant load systems to some extent. This section characterizes the difference in energy savings between constant and variable load systems, within each application. To address this question, the team modeled the theoretical energy consumption of each pump as if controlled using two different methods: throttling the system (i.e., constant speed flow control) and changing the speed of the pump (i.e., variable speed flow control).

### 3.3.1. 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. Figure 6 illustrates a performance curve and shows that as the pressure in a system increases, the flow in the system decreases. Practitioners use this phenomenon to control the flow rate of water through a system by increasing system pressure through "throttling." This control approach is effective in decreasing flow, but results in higher operating pressures in the system and higher than necessary energy use.

**Figure 6. Example of a Pump Performance Curve**




Using the load profile for each pump as identified in Section 3.2, 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 at each load point. 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.

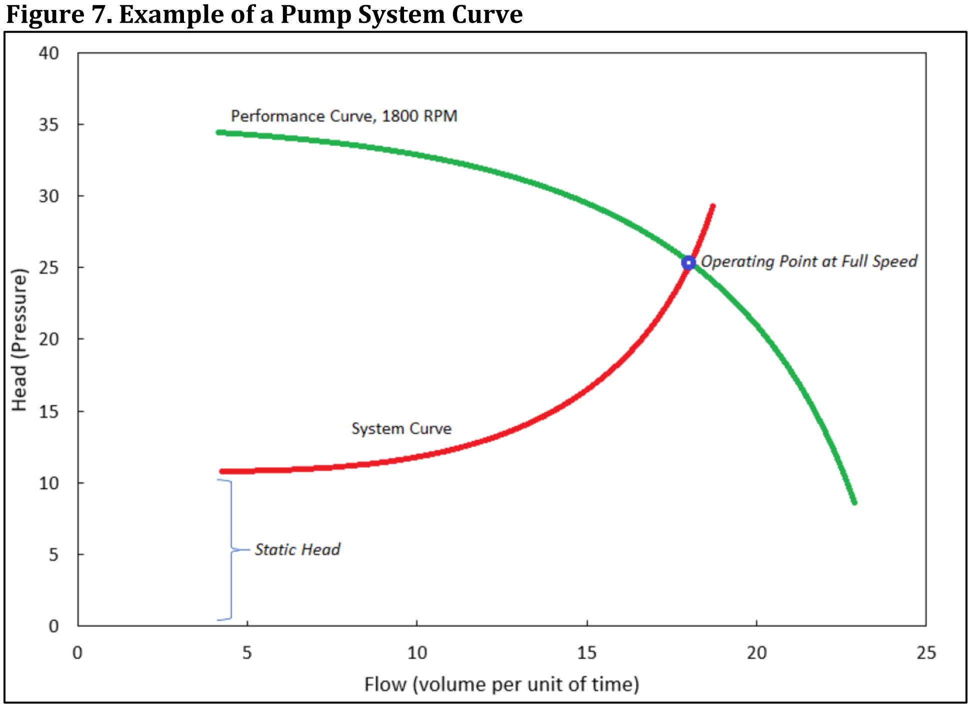
The next section discusses how the team calculated energy consumption for pumps with variable speed control.

### 3.3.2. 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, many more factors impact the relationship between flow and pressure.

The relationship between flow and pressure shown in Figure 6 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 7. The system curve for each application is unique, as it is based on two parameters: (1) the static head in the system and (2) the operating point at full speed (i.e., where the system curve and the pump curve at full speed intersect).

**Figure 7. Example of a Pump System Curve**




To model the energy consumption of each pump using variable speed control, the research team made some basic assumptions regarding typical system static head and the operating point at full speed.

#### *3.3.2.1. Static Head Assumptions*

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. Closed loop systems are largely unaffected by static head because they are circuits in which with suction pressure is equivalent to discharge pressure. However, in open loop systems the static head can have a large impact on the power draw of the pump, especially at lower flow rates. Because of these differences in static head by system type, closed loop applications (commercial chilled water loop and commercial heating) were estimated to have no static head. For other applications, the static head used the values measured in NEEA's XMP research, shown in Table 2.[4]

**Table 2. Static Head Used in Analysis**

| NEEA XMP Research Application | Static Head (% of head at BEP) |
|---|---|
| **Commercial Cooling Tower** | 35% |
| **Commercial Pressure Boost** | 35% |
| **Industrial** | 22% |
| **Municipal** | 22% |

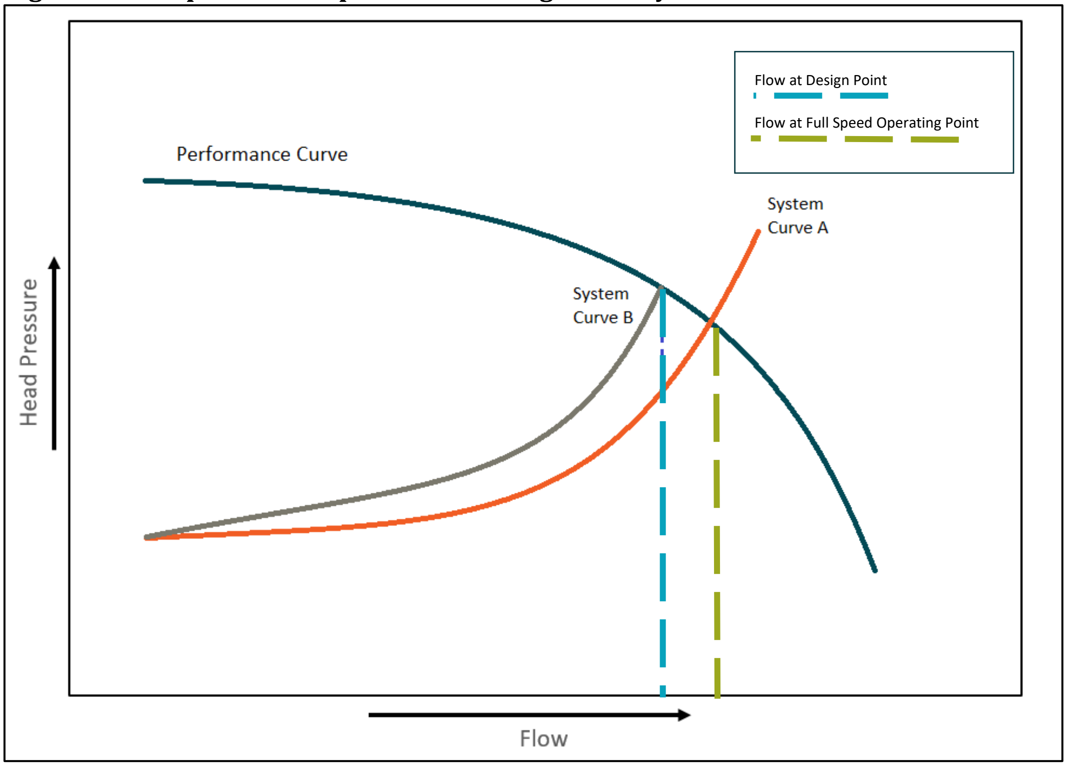
#### *3.3.2.2. Full Speed Operating Point Assumptions*

The operating point at full speed represents the intersection between the system curve and the performance curve. In an ideal pump installation, the system curve intersects the performance curve at BEP. Of course, ideal design rarely occurs. Even if a system specifier initially selected the pump with the operating point at BEP, they will often provide conservative system pressures when scoping pump systems (an oversized system can be throttled to provide the desired flow, but an undersized system that cannot meet the needed flow would have to be replaced with a larger system). This oversizing causes pumps to operate further to the right of BEP (providing more flow) than necessary.

To account for this, in a constant load system, an operator hires a contractor to analyze the system and throttle it back to provide the design flow rate at the specified head, as described in Section 3.3.1 (referred to as system "balancing"). The problem is that the required balancing valves artificially introduces head into the system, which creates a new operating point different than the "native" full speed operating point that would exist without throttling (i.e., all control valves open). This is important because one of the major sources of energy savings from variable speed control is decreasing system pressure through opening valves and instead controlling the pump by reducing the speed. Figure 8 shows the difference in head pressure when a system is throttled away from the full speed operating point. In this diagram, System Curve A represents the system curve at the "native" full speed operating point. System Curve B represents the system curve when a system is throttled to meet a specific flow at full speed. The difference between the pressures indicated in blue represents the pressure added to the system by throttling.

[4] While some industrial pumping systems are closed loops, the team did not have information on which systems were closed loop and which systems were open loop, so the industrial static head value was applied to all industrial pumps included in the analysis.

**Figure 8. Example of the Impact of Throttling on the System Curve**




The existing data do not include information on the non-throttled, full speed operating point and how that point relates to the required system design point. Therefore, to calculate the savings associated with variable speed control, the team used the maximum flow rate observed in the data as the design point for the system and assumed that the pump was being optimally controlled. Using the maximum flow as design point 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. However, the data available from the NEEA XMP Pump Research study do not contain information on the design flow rate and ideal system operating point, and these data are not easily obtained.

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.[5]
- For pumps in NEEA's dataset equipped with variable speed drives for which operational speed data are not available, the team assigned the full speed operating point (the point at which the system curve intersects the performance curve) as the maximum flow rate observed in the data (which *was* available). As it is unlikely that pumps would operate above the design point, the team also presumed the design point is equivalent to maximum observed flow rate (and, therefore, full speed operating point), which implies that there is

[5] In all cases for which operational speed data exist, the maximum speed of the motor is known.

no throttling in the system and that the drive is used to control the pump flow rate by changing speed. Energy savings and speed reductions are then possible for any flow points below the full speed operating point.

- For pumps that are not equipped with drives (i.e., constant speed pumps), whether on constant load or variable load systems (that is, applications that operate at primarily a single duty point or a range of duty points), the team relied on analysis from the Department of Energy (DOE) to inform the relationship between the design point (where the system is actually operating) and the full speed operating point (where the pump would operate with no throttling present in the system). 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 analysis 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 (see Figure 5). 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 as discussed above, in the case of these constant speed pumps with observed flow rates very near to or greater than 100% of BEP flow, the maximum observed flow is also presumed to be equivalent to the design flow. This implies that the system is unthrottled and that limited, or no oversizing existed in the system. This latter assumption applied 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.

The assumptions made to calculate the energy consumption using variable speed load control represent a large limitation in the data used to develop this analysis, and the analysis presented above reflects only one possibility for the relationship between the system design point and the actual full speed operating point as installed. Variations in the full speed operating point, as it relates to the required system design point, have the potential to drastically impact the energy savings from installing a PDS, especially in constant load systems. Because this represents a significant source of uncertainty in the analysis, the team performed a sensitivity analysis on the energy savings that would result from installing a PDS on such systems. The sensitivity analysis explored two scenarios:

1) On the high savings end, the team assumed that the pump's full speed operating point as installed was 10% above the operating point assumed in the default case presented above. That is, the analysis assumed 10% *more* oversizing or throttling in the system than initially assumed. For pumps with variable speed drives and constant speed systems with maximum flow rates above the default 92.5% of BEP flow, this equates to a full load operating point 10% greater than the observed maximum flow rate.[6] For constant speed pumps that used the default sizing assumption, this assumes that the full speed operating point is approximately 102% of BEP flow.
2) On the low savings end, the team assumed that the full speed operating point was either equivalent to the design point (so no oversizing savings are available) or on the low end of the range provided by DOE (listed previously). Table 3 summarizes the assumptions

[6] Except for variable speed pumps already operating at full speed, where the full load operating point is capped at the full speed operation of the motor/drive.

associated with the full speed operating point for different types of pumps. Section 3.3.4 investigates the sensitivity of the analysis to changes in these assumptions.

**Table 3. Full Speed Operating Point Assumptions for Default Analysis Case and Sensitivity Scenarios**

| Pump Case | Full Speed Operating Point Assumption | | |
|---|---|---|---|
| | **Default Analysis Case** | **High Savings Scenario** | **Low Savings Scenario** |
| **Variable Speed Pumps with Speed Data** | Head and Flow associated with next highest nominal speed case (1750 or 3450 rpm) | Head and Flow associated with 10% increase in flow on full speed pump curve | No change |
| **Variable Speed Pumps without Speed Data** | Head and Flow associated with maximum observed flow rate (i.e., design point) | Head and Flow associated with 10% increase in flow on full speed pump curve | 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 |
| **Constant Speed Pumps with Maximum Flow Above 92.5%** | 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) |

### 3.3.3. Energy Savings

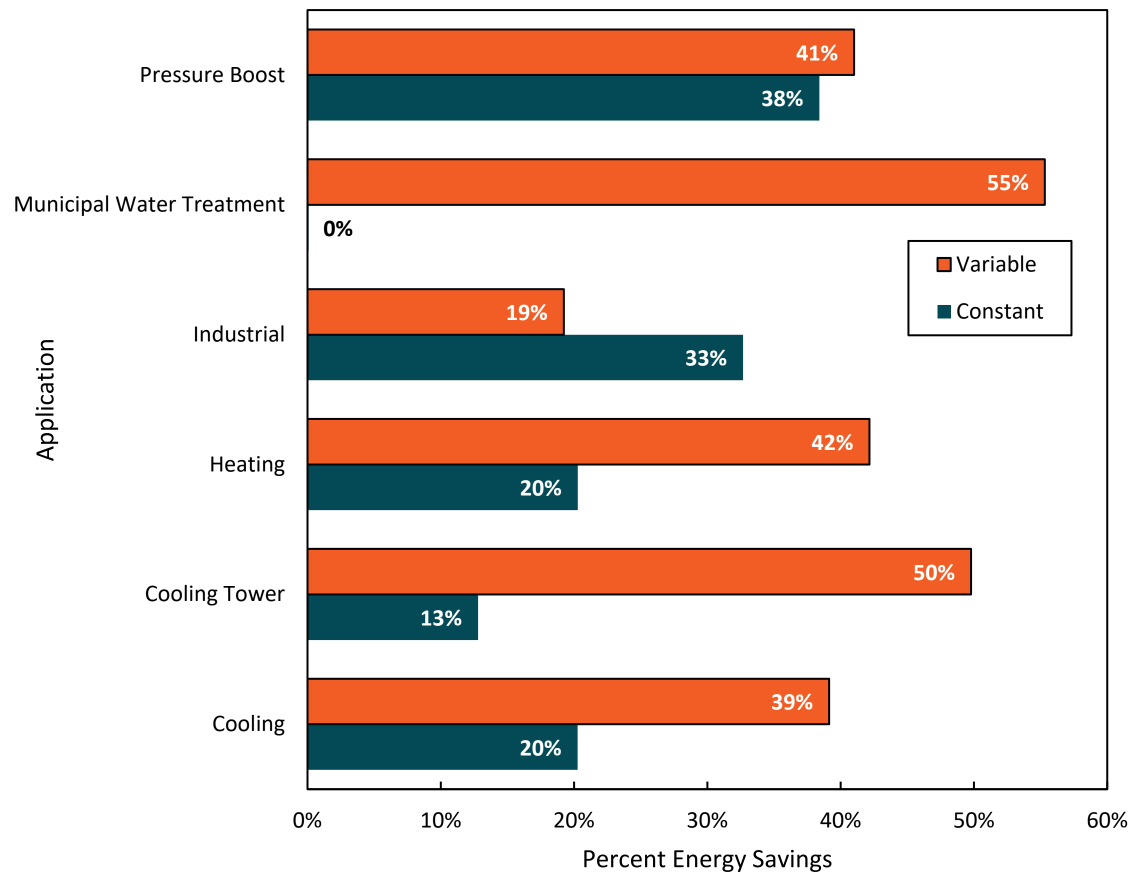
The differences between the weighted average power draws for the different flow control methods represent the energy savings from the addition of a PDS. From an aggregated perspective, the percent power savings for variable load systems are approximately double that of constant load systems, as shown in Table 4.

**Table 4. Average Power Difference between Constant Speed and Variable Speed Control, Normalized to Motor HP**

| Load Type | Average of Power Difference Normalized (kW/HP) | Percent Energy Savings |
|---|---|---|
| **Constant** | 0.194 | 23% |
| **Variable** | 0.240 | 43% |

Looking at these average data, the energy savings available from variable load systems are approximately 23% larger than the energy savings from constant load systems. However, the magnitude of those savings varies considerably depending on the application.  Figure 9 explores the energy savings from inherently constant and inherently variable load systems for the six pumping applications presented in Section 3.2.

**Figure 9. Percent Power Savings by Application and System Load Type**




The analysis showed no energy savings in constant load municipal applications, due to the way pressure boost pump systems operate. As mentioned in Section 3.2, operators at municipal water treatment facilities often install pumps in pairs, with a constant speed pump that handles the base load and a pump with a PDS attached that manages fluctuations in the load. This set-up allows the control scheme to operate the constant speed pump at 100% of the duty point all the time, while the variable speed trim pump turns on, off, and varies speed based on demand. This results in zero observed power savings for these constant load pumps. However, savings are available from equipping all pumps on a pressure boost skid with PDS. 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).

As shown in Figure 9, variable load savings are larger than the constant load savings in all applications except industrial. The difference varies by application, ranging from less than two times the savings in commercial pressure boost applications to approximately four times the savings in more inherently variable commercial cooling tower applications.[7]

To summarize, the results in Figure 9 confirm the common perception that PDSs have tremendous potential to save energy in variable load systems. However, the results *also* demonstrate that *even* for constant load systems, significant energy savings are possible. 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, the normalized cost of a VFD is approximately $35/HP (ATO, 2019). Based on this, a VFD installed on a constant load commercial HVAC system would have a simple payback of approximately 10 months.

### 3.3.4. Sensitivity Analysis

The energy savings calculated in the analysis make a strong case for installing PDSs on both constant load and variable load systems. To better determine the real-world energy savings, the team needed to calculate a system curve. Two variables, static head and full speed operating point, are intrinsic to calculating the system curve and can have a large impact on the energy savings *actually* available through reducing the speed of a pump. Because of this, the team performed independent sensitivity analyses on these two variables to quantify the impact each has on the energy savings estimate.

For sensitivity analysis on the static head assumption, the team established a range centered on the static head observed in NEEA's XMP Pump Research, with the lower bound being 50% less and the upper bound being 50% more than the average values, shown in Table 5.

**Table 5. 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 | | |
| **All Other Applications** | 11% of Head at BEP | 22% of Head at BEP | 33% of Head at BEP |

Similarly, to assess the impact of fluctuations in full speed operating point on the energy savings, the team again established a range of values. As mentioned in Section 3.3.2, DOE's pump analysis established a range for full speed operating point based around BEP (presented in Table 3).

#### *3.3.4.1. Energy Savings Sensitivity to Static Head Assumptions*

Table 6 shows the impacts of variations in the static head on the energy savings (the analysis assumes no static head in closed loop systems, so Table 6 does not include commercial chilled water and commercial heating). The energy savings range from 23% to 31% in constant load systems and from 40% to 55% in variable load systems. 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.

[7] For the purposes for this comparison, applications without both constant and variable load savings were left out (municipal water treatment pumps).

**Table 6. Percent Energy Savings Calculated with a 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% |
| **Industrial** | 30% | 35% | 17% | 21% |
| **Municipal Water Treatment** | 0% | 0% | 50% | 60% |
| **Pressure Boost** | 31% | 46% | 33% | 49% |
| **Average** | **23%** | **31%** | **40%** | **55%** |

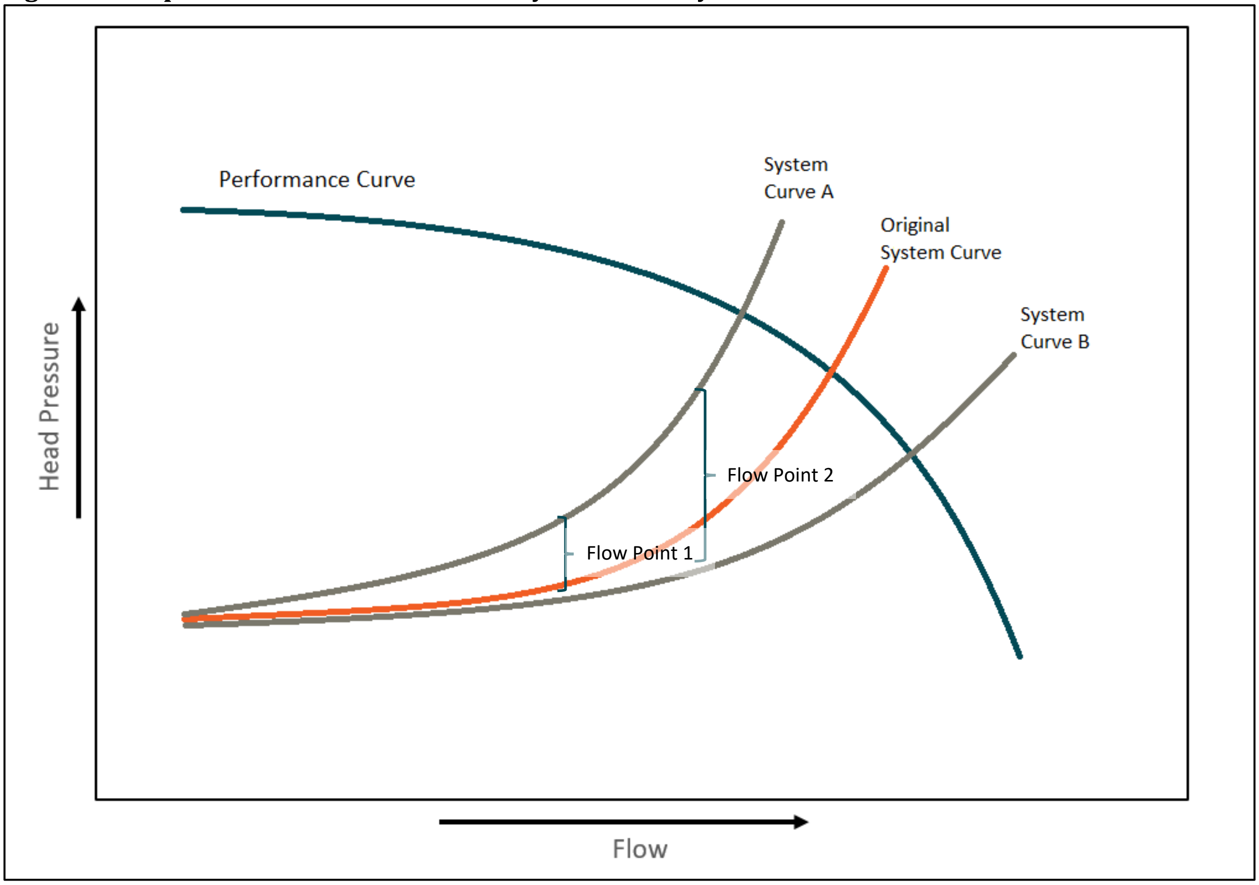
#### *3.3.4.2. Energy Savings Sensitivity to Full Speed Operating Point Assumption*

Table 7 presents the impact variations of the full speed operating point on the energy savings of a pump. For constant load systems, the impact on energy savings is almost negligible. While there is a small difference in the energy savings on average, half of the applications saw a difference between the high and low limit of less than 1%, and no application had a difference greater than 2%. For variable load systems, the energy savings on average range from 40% to 45%, with heating yielding the broadest range, at 36%–47%. On an individual pump level, the broadest range is between 38%–75% energy savings, seen on a variable load cooling tower pump. The variability of the energy savings here, again, is driven by where on the system curve the pump is spending most of its time. As is shown in Figure 10, the lower flow rate ("Flow Point 1") has less of a difference between the head pressures of the different system curves than is seen at higher flow rates ("Flow Point 2"). 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.

**Table 7. 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% |
| **Industrial** | 31% | 33% | 19% | 19% |
| **Municipal Water Treatment** | 0% | 0% | 54% | 56% |
| **Pressure Boost** | 37% | 39% | 40% | 42% |
| **Average** | **22%** | **23%** | **40%** | **45%** |

**Figure 10. Impact of Flow Rate on Variability in Sensitivity**




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 impedes calculations of the exact energy savings and payback periods from installing drives in constant and variable load applications.

Research into pump system design and sizing would significantly help characterize this uncertainty. The research could consist of two data collection strategies: (1) field research and (2) interviews with contractors. The field research would include identifying systems for which the characteristics at installation are known (native head within the system) and monitoring them to determine the operating pattern of the pump and real potential for pump right-sizing when installing a variable speed drive. The research would include both constant load and variable load systems, to investigate differences in sizing for pumps serving different types of loads. The second data collection method would leverage the experience of contractors in balancing systems. Testing, Adjusting, and Balancing (TAB) contractors and water balancers specialize in balancing systems based on the required flow and installed operating needs. Surveys of these contractors would illuminate trends in sizing and throttling across applications and industries.

## 3.4. Are applications already taking advantage of PDS savings for both constant and variable load systems?

Section 3.2 demonstrates that even constant load applications, on average, have reasonable payback periods. This finding led the team to explore whether installers are already recognizing this and installing PDSs on systems serving constant loads.

Table 8 shows the pumps by application and load type, but also separates the pumps by the presence of a PDS. Disaggregated in this manner, some interesting trends become apparent.

**Table 8. Count of Pumps, by Load Type, Presence of a PDS, and Application**

| | Commercial HVAC | | | | | |
|---|---|---|---|---|---|---|
| **Load Type** | **Chilled Water Loop** | **Commercial Cooling Tower** | **Heating** | **Commercial Pressure Boost** | **Industrial** | **Municipal Water Treatment** |
| **Without PDS** | **4** | **3** | **10** | **8** | **8** | **0** |
| **Constant Load** | 4 | 2 | 8 | 7 | 7 | |
| **Variable Load** | | 1 | 2 | 1 | 1 | |
| **With PDS** | **50** | **28** | **9** | **6** | **2** | **4** |
| **Constant Load** | 21 | 9 | 7 | 4 | 1 | 1 |
| **Variable Load** | 29 | 19 | 2 | 2 | 1 | 3 |

The nature of the data used for this analysis precludes comparisons across drive types (with/without PDS);[8] however, of the pumps with a PDS installed, more than half (58%) are on constant load systems, clearly indicating that the benefits of right-sizing are not lost on pump purchasers or installers. The application of PDS to constant load systems is most evident with commercial chilled water loops. Recall that analysis in Section 3.2 showed these pumps had significant potential for energy savings from right-sizing; 42% of the pumps with PDS in those applications are constant load pumps. This suggests engineers designing chilled water systems recognize the energy savings from right-sizing and incorporate PSD into the design.

Looking at the pumps without PDS installed, only 15% of the systems are variable load. This indicates that it is uncommon, at least in pumping installations, for systems that require variable flow to not have a PDS. Five of the pumps analyzed operate on variable loads and do not have a PDS. Four of these systems spend 90% or more of their time at two load points and 60% of their time at one load point, indicating that while they are variable as defined in this analysis, they do have consistent operating points, relative to the other systems.

[8] NEEA's XMP Pump Research did not collect a sample of pumps representative of the distribution with and without PDS, nor did the research collect an equal number of pumps with each drive type. Comparing the distribution of pumps, by load, across the drive type inaccurately represents the market as a whole.

## 3.5. How can the energy savings findings be applied to other applications?

The energy savings analysis presented in this white paper focuses on pumping applications. Pumps make up a large portion of industrial electric motor energy consumption in the Pacific Northwest, with approximately 17% of motor energy consumed by pumps (NWPCC, 2016).[9] Nonetheless, this leaves most motor applications and energy uses unaddressed.

The energy savings from PDS installed on pumps are from both load matching and right-sizing. These energy savings mechanisms are applicable to other variable torque applications, such as fans and compressed air. Fans operate similarly to pumps, serving loads that are dependent on external forces such as temperature or building occupancy. These systems can either have variable load profiles or meet an operating point that is away from the design point. In total, variable torque applications represent 33% of Pacific Northwest motor energy use (NWPCC, 2016).

Applying the findings to constant torque and constant horsepower systems requires more nuanced consideration. Pumps, fans, and compressors are crosscutting (i.e., they are present in almost all commercial building types and industries), which allows the use of generalized data to address energy savings across sectors. Material handling and material processing, which comprise most constant torque and constant horsepower systems, are concentrated in industrial applications. An analysis that estimates the energy savings of constant torque and horsepower systems requires a better understanding of these applications' load profiles and operating needs. However, material handling and material processing are often directly linked to industrial production, and benefits that affect production can often generate a larger monetary impact than can energy savings. These types of benefits are discussed in the next section.

[9] This information is specific to the industrial energy use in the Pacific Northwest. While the energy consumption of pumps varies by industry and the saturation of specific industries differs across the country, the team felt that a regional number would present a reasonable approximation. A reviewer can use information from the US Energy Information Administration (EIA) to confirm this estimate.

# 4. Non-Energy Benefits of Power Drive Systems

PDSs produce benefits that are less easily quantifiable than the energy savings presented in Section 3. These non-energy benefits can have larger impacts on a facility than do energy savings. 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). This section aims to characterize the different non-energy benefits, their impacts on different systems, and to provide a general methodology for quantification.

In a survey of both scientific and manufacturers' literature, the team found that most non-energy benefits are grouped into three categories: decreased maintenance, process improvements, and system connectivity (Tamez, 2019). This section discusses each of these categories and the impacts a PDS can have on a system.

## 4.1. Decreased Maintenance

The cost of labor in commercial and industrial facilities has followed a steady upward trend for the last 70 years that is predicted to continue to increase (US Bureau of Labor Statistics, 2019). This trend of rising labor costs makes decreasing the amount of time spent servicing equipment a benefit that will only increase with time. PDSs not only provide the ability to operate a motor more efficiently, but they also allow motors to operate in a manner that prevents wear and tear on the equipment. By allowing a system operator to decrease both the cost of replacement parts and the labor cost associated with maintenance, PDSs can provide a cost reduction separate from energy savings, which can justify its cost.

A PDS creates two main methods for decreasing maintenance cost: soft starting and maintaining performance. Both provide savings to a facility through reduced maintenance costs and reduced replacement equipment costs.

### 4.1.1. Soft Starting

An extended motor product experiences a sudden inrush of current upon motor start-up. This rapid start creates a spike in torque and system pressure as the motor starts to move a previously inert load. These spikes, when they occur every time a motor is turned on, cause mechanical shock to the motor and can result in damage to the extended motor product (EATON, 2013). Installing a "soft starter" mitigates these stresses. In an electrical system, a soft starter directly precedes the motor (the same spot as an adjustable speed drive (ASD), which is the drive part of a PDS) and slowly ramps up the current allowed through the system to the motor. This allows the motor to slowly increase its speed and avoid spikes in torque. Eliminating these torque spikes not only removes a source of wear and tear on the system, but can also reduce active power (power consumed by turning the motor) up to 19% (de Oliveira, Nied, Santos, & Dias, 2011).

The direct purpose of an ASD is to increase and decrease the speed of a motor. With this capability, many manufacturers program ASDs to slowly increase the speed of rotation upon motor start-up, allowing them to serve as soft starters for motors.

Many motor users view soft starters as an alternative to installing an ASD. Soft starters are usually less expensive than ASDs. Comparing the two types of equipment from the same manufacturer, for mid-size motors soft starters can range from $35/HP for a 10 HP motor to $10/HP for a 100 HP motor, whereas ASDs over the same size range span $45/HP to $30/HP. While incrementally more expensive on a first cost basis, PDSs not only provide soft starting capabilities, but also enable one to right-size a motor to the application or control the system more efficiently, providing a wider range of utility.

### 4.1.2. Maintaining Performance

In contrast to stand-alone soft starters, PDS also offer the ability to dial in the system's operation while it is running to prevent large maintenance costs from occurring early in the life of a piece of equipment. Maintaining the performance of a motor allows a longer useful lifetime for the equipment, prevents downtime for repair that could impact production, and decreases the manpower needed to maintain the equipment. These benefits can have huge impacts on the total cost of operation for a facility, both in decreasing the resources needed to support the equipment and in reducing possible production downtime.

The benefits from maintaining equipment performance are not as easily quantifiable as the energy savings associated with a PDS. They depend on previous motor operation, the prior level of required operator involvement, and the lifetime of the extended motor product. According to one study, applying PDS to pumps in a pipeline increased the average time between repair events by 25% (Ferrari, 2016). In another case study, eliminating throttling in pumping systems decreases the wear on the system by decreasing the pressure applied to the pipes and valves, in turn lowering the maintenance costs required to maintain the control system by 80% (a comparison of the costs to maintain and repair a throttle valve vs. the costs to maintain a PDS) (ABB, 2011).

## 4.2. Process Improvements

Next to decreased maintenance, the most-cited PDS non-energy benefit for pump and fan systems is process improvements. The ability for an industrial facility to better control a process' operation has the potential to provide larger financial benefits than does a decrease in energy consumption. Beyond the savings value itself, capital expenses that directly impact revenue are often easier expenditures to justify. Adding the functionality to automatically change motor operation allows for better process control, increased production, system flexibility, and the ability to monitor a system through the "internet of things". All three of these benefits directly impact the production of the plant. The following subsections outline these benefits.

### 4.2.1. Improved Control

Industrial facilities use PDS to control processes that either precede or follow production equipment, which allows them to operate precisely at the required design point. Process optimization allows for the highest quality end product, which drives up profits, benefits the end-user, and increases the quality associated with a brand (ABB, 2011).

One case study illustrating this benefit featured a wood saw process line at a lumber mill. In the process, a conveyor belt transports logs from the storage facility to a wood saw, drives the log through the saw, and then transports it to the next step of the process. Applying a PDS to this process enabled logs to be transported at a higher speed from the storage facility to the saw, then slow down to the ideal cutting rate for the saw as the log was cut, then speed up again once the log was through the saw (Wiedenbrug & Sanford, 2012).

### 4.2.2. Increased Production

The lumber mill example used for improved control in Section 4.2.1 also illustrates the potential of a PDS to increase production. Since different pieces of process equipment operate at different rates, the ability to ramp up and down portions of a manufacturing process—but not all portions simultaneously—to meet these different production rates unlocks the opportunity to increase yield. Impacts from increased production are specific to each process but are not dependent on the torque/speed relationship.

### 4.2.3. System Flexibility

PDSs provide the ability to plan for future increases in production. Systems that operate constant speed pumps can be (and often are) oversized to provide a safety factor or the ability to handle increases in load. However, a large increase in a facility's capacity requires costly changes to the system. A large portion of these costs come from the addition of more motor-driven equipment to the facility (ABB, 2011).

By comparison, if a design engineer leverages the variable speed capabilities of PDS when planning a facility, the system can either be drastically oversized and still operated efficiently, or have multiple pieces of equipment installed and operated at part-load operation to extend the life of the equipment by decreasing mechanical loading.

### 4.2.4. Internet of Things

Traditionally, control systems were local to a facility and connected to equipment by physical wires (e.g., 4-20 mA process control loop). Modern controllers will increasingly be web-based, enabling manufacturers to incorporate industrial equipment (such as a PDS) into the Internet of Things (IoT).

The move to integrate extended motor products with IoT has already started. The pump industry touts smart pumps, or pumps with an integrated PDS and control logic pre-programmed into the unit, as the next revolution in the pumping world. These smart pumps are often IoT-enabled by digitally linking them to monitoring systems or allowing access to pump operational information on mobile devices. Even if a pump does not have the integrated sensors of a Smart Pump, a non-integral PDS will have sensors or actuators connected to the motor, which allows for power draw and speed data collection. Feeding these data to a cloud server provides the ability to make real-time changes to a motor system remotely.

Smart equipment in an IoT landscape promises real-time optimization of the system, enabling a motor owner to more effectively realize the other benefits presented in this paper. Two primary benefits to incorporating PDS into the IoT include using non-production data to improve product longevity and using production-related data to improve operation. Both are benefits previously mentioned above (decreased maintenance and increased production), and connection to IoT allows quick changes to the system, made without human interaction.

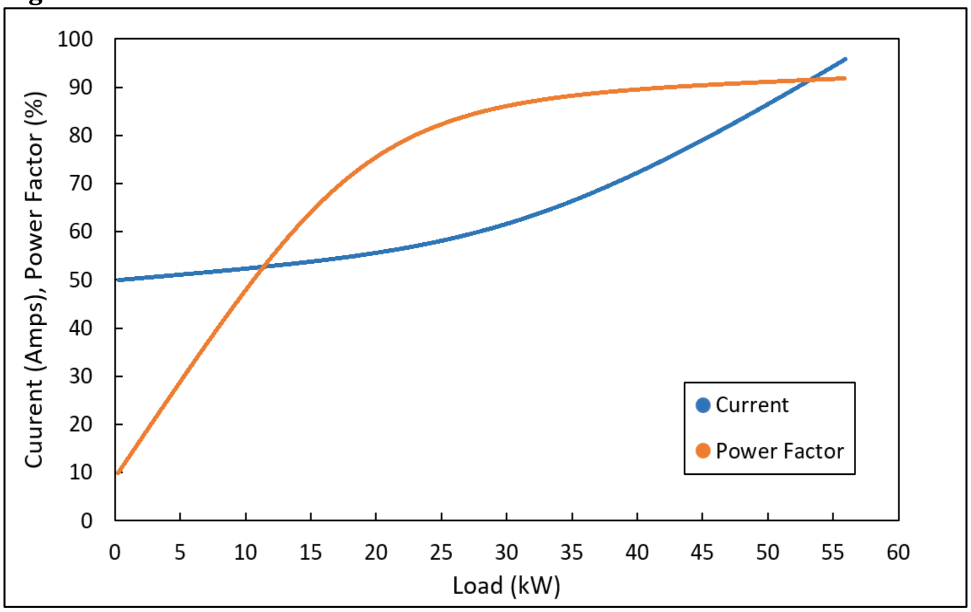
# 5. Other Energy Benefits of Power Drive Systems

In addition to load matching and right-sizing, two other energy benefits associated with PDS were consistently mentioned in the literature: power factor correction and regenerative drive application.

## 5.1. Power Factor Correction

Power factor is the ratio of the real power used to do work (e.g., rotate a rotor) to the apparent power supplied to the circuit. A higher power factor represents better utilization of electric power. AC induction motors are notorious for having lower than average power factors, and power factor becomes especially low when a motor is oversized and operating with a light load (Peltola, 2017). Figure 11 illustrates the relationships between current and load and between power factor and load.

**Figure 11. Line Current and Power Factor as a Function of Load**




As discussed in Section 3, motors installed in variable torque applications are systemically oversized. This presents a great opportunity to save energy by improving the power factor of a motor. Certain AC Variable Speed Drives (Pulse Width Modulating drives, or PWM drives) incorporate rectification which can increase the power factor to 5%–10% better than a bare motor (Prachyl, 2010), which may result in additional energy savings (beyond those presented in Section 3).

## 5.2. Regenerative Drive Applications

PDSs also offer the ability for an AC motor to operate as a generator when the load it is serving is moving beyond the force of the motor. The basic definition of a generator is a piece of equipment that converts mechanical power to electric power. When a motor's load is moving faster than the motor, a PDS can harness that energy and send it back to the utility company or utilize it directly by other equipment if the system is set up as a common bus (Prachyl, 2010). Installations of these systems are most common on elevators, centrifuges, hoists, and cranes (Raghava & Naik, 2014). All these applications have the unique ability to take the machine's utility (which in these cases is imparting momentum to other objects for the purpose of moving them) and leverage it to generate power. This is a similar principle to the regenerative energy system used in electric vehicles.

Weight-moving equipment often has braking resistors, which dissipate the excess energy when a system overruns a motor. If the electronics do not dissipate the excess energy, it can cause a drive failure. Bussing multiple drives together in a regenerative drive system allows for energy to flow between the drives and motors, enabling a motor to use the energy generated by another motor. This configuration presents a great opportunity for energy savings for situations in which equipment is operating at the same time but handling opposite loads, such as a set of escalators, where one escalator is descending (a loaded escalator may overtake the motor) and one escalator is ascending. If the option to use the regenerated energy right away is not present, line regeneration uses a converter wired to the bus to allow for energy output back to the grid.

# 6. Steps to Promote PDS in all Applications

The value proposition for PDS installations differs based on the motor's application. This range of benefits hampers the ability to succinctly describe the benefits or to target marketing material to increase PDS adoption. As the team conducted the literature review and started to identify non-energy benefits, two questions arose: Are manufacturers using non-energy benefits to market PDS, and are non-energy benefits a driver in increasing the market penetration of PDS? This section looks more closely at those questions.

## 6.1. Are manufacturers marketing PDS with non-energy benefits?

While manufacturers are clearly promoting the energy benefits of PDS—at least four manufacturers host online energy savings calculators to support justifying the purchase of a PDS—the team investigated whether manufacturers also showcase the non-energy benefits of PDS. The four manufacturers that host calculators also use non-energy benefits in their marketing materials. Siemens' website, for example, has five different case studies that present both the energy and non-energy benefits for different applications. A third-party review of manufacturers' marketing materials found that of the five manufacturers included in the review, three included more than 15 non-energy benefits in their marketing literature, and all five included at least four non-energy benefits (Tamez, 2019). The next step in marketing non-energy benefits is incorporating them into the manufacturers' savings calculators.

## 6.2. Are non-energy benefits a driver in increasing the market penetration of PDS?

Even with the increased adoption of PDS and the generally-accepted view that market penetration is increasing rapidly, little data on the PDS market is publicly available. In 2002 DOE published the Industrial Electric Motor Systems Market Opportunities Assessment, which estimated that the installation of variable speed drives was increasing at a rate of 5% per year (DOE, 2002). DOE fielded a study to update this assessment in 2018 and 2019, but had not yet published it during the development of this white paper. To confidently address this question the team needs two pieces of information: updated market penetration data for PDS and research targeted at investigating the purchasing habits surrounding PDSs.

## 7. Conclusions

While it is commonly accepted that Power Drive Systems can save significant energy in certain applications, this paper shows that PDSs 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 PDSs, represent key barriers to greater PDS adoption.

The research team's analysis of pump operational data showed that none of the applications researched in NEEA's XMP Pump Research are intrinsically constant load applications. This implies no industry or application should rule out adding a drive to a pump based on the application type, even those considered constant load a priori. In this analysis, the team also found 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 9. Notably, savings from installing a PDS in a constant load system averaged 23% with a payback of 10 months. This implies that a PDS will most likely produce energy savings in any application, regardless of the load.

**Table 9. Summary of Energy Savings and Payback Period for Constant Load and Variable Load Systems**

| System Type | Savings | Payback Period |
|---|---|---|
| **Constant Load Systems** | 23% | 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 PDSs 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 research pump sizing methods as they relate to static head and full speed operating point. 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 wider-than-appreciated suitability of PDS.

In addition, more work is needed to extrapolate these findings to other applications. While the team believes the findings from the pump analysis are representative of other variable torque applications, more detailed review of fan and compressor 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 reviewed in this paper, which may outweigh the energy savings 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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