Central HVAC Advanced Electric Motor Lab Evaluation

Final Report

ET23SWE0065

Source: ABB Motors Product Manual

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Disclaimer

Executive Summary

This report presents the findings of a field evaluation of advanced electric motor technology in a central HVAC hydronic pumping application. Conducted by the Western Cooling Efficiency Center at the University of California, Davis, the study compares the performance of ferrite-assisted synchronous reluctance motors against standard National Electrical Manufacturers Association premium induction motors in a real-world building environment.

The evaluation was motivated by prior laboratory testing that demonstrated significantly higher part-load efficiency for ABB's ferrite-assisted synchronous reluctance product "Baldor EC Titanium." Part-load efficiency is important in HVAC systems where equipment often operates well below full load. Dutton Hall, a 47,459-square-foot administrative office building on the UC Davis campus built in 1998, was selected as the test site due to its representative variable air volume with terminal unit hydronic reheat HVAC system and compatibility with the study's requirements.

Four hydronic pumps were installed, pairing one ferrite-assisted synchronous reluctance motor and one standard motor serving both heating hot water (HHW) and chilled water (CHW) loops. The motors were operated in parallel and energy performance was monitored using both building management system data and Western Cooling Efficiency Center instrumentation.

Key findings include:

Energy Savings

Heating Hot Water System

- The EC Titanium motor reduced measured energy use by 18 percent, with an expected simple payback of 0.34 years for motor additional equipment cost only, or 3.3 years including the full equipment cost of a new variable frequency drive, assuming $0.39/kWh tariff.
- Calculating the baseline motor energy consumption to correct for asynchronous motor slip as if it pumped water at the same rate as the EC Titanium motor increases the predicted energy savings to 28 percent. This would result in a simple payback of 0.25 years for motor equipment cost premium or 2.4 years including the full equipment cost of a new VFD.

Chilled Water System

- The EC Titanium motor reduced measured energy use by 17.9 percent, with a simple payback of 2 years for motor additional equipment cost only, or 5 years including the full equipment cost of a new VFD.
- Adjusted for the same flow rates, the CHW savings are 18.9 percent which results in a payback of 1.3 years for the motor equipment cost premium; adding the full equipment cost of a new VFD the simple payback would be 4.4 years.

Installation and Commissioning

The advanced motors were compatible with standard pump mounts and required minimal changes to installation procedures. Electricians noted minor differences in VFD setup, but no additional training or tools were needed.

Stakeholder Feedback:
UC Davis Facilities Management staff and distributors responded positively to the technology, citing ease of integration and interest in broader adoption. Engagement with energy program implementers and the California Technical Forum suggests strong potential for inclusion in future efficiency programs.

This study demonstrates that ferrite-assisted synchronous reluctance motors can deliver meaningful energy savings in hydronic HVAC systems with minimal changes to standard retrofit practices. The results of this project support further deployment of this technology and provide a foundation for utility program development, a comparison for future energy savings simulation estimates, and are a resource for contractor training.

Acknowledgements

The authors would like to thank the UC Davis facilities team for building access, installation, and technical support with controls.

Abbreviations and Acronyms

Acronym	Meaning
AC	Alternating current
BMS	Building management system
CHW	Chilled water
DC	Direct current
DOE	Department of Energy
EC	Electronically commutated
EOLDP	End of line differential pressure
EMF	Electromotive force
FASR	Ferrite-assisted synchronous reluctance
HHW	Heating hot water
HP	Horsepower
HVAC	Heating, ventilation, and air conditioning
IEA	International Energy Agency
NEMA	National Electrical Manufacturers Association
PI	Proportional integral control
PM	Permanent magnet
PMSynRM	Permanent magnet synchronous reluctance motor
RPM	Rotations per minute
RTU	Rooftop unit
SR	Synchronous reluctance
UC	University of California

Acronym	Meaning
VAV	Variable air volume
VFD	Variable frequency drive
WCEC	Western Cooling Efficiency Center

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Introduction

The 2022 Commercial End Use Survey showed that hydronic heating and cooling systems serve approximately 1.6 billion square feet in California [1]. This is the most common heating or cooling system for large office buildings and the second most common for all commercial buildings. While there are opportunities for highly efficient motors in all systems, this report focuses on water pumping for hydronic heating and cooling. A typical hydronic system uses a central plant to chill or heat water which is distributed by pumps to air handling units and reheat coils. The minimum efficiency and controls for these pumps is mandated on a state level. In California, Title 24 Part 6 Section 140.4 sets prescriptive requirements for hydronic systems; most other states adopt some version of the ASHRAE 90.1 standard. These standards require motor efficiency to be above a minimum threshold with variable speed controls for systems 5 HP and above. At a national level, the US Department of Energy (DOE) mandates a minimum efficiency of “premium” by the National Electrical Manufacturers Association (NEMA).

All NEMA Premium motors must meet a relatively high full-load efficiency based on the frame and number of poles. Five motors tested by the Western Cooling Efficiency Center (WCEC) in a previous project all met the minimum with the EC Titanium motor differing by a few percent at full load [2]. However, when operated at less than full load, the differences are much more pronounced. For example, the most efficient motor tested was the ABB EC Titanium with 85 percent efficient at 50-percent load, while the least efficient was 71 percent. At 30 percent load, the difference is even greater: 73 versus 43 percent. Both motors were the same horsepower and frame size.

These results motivated WCEC to explore energy saving applications for emerging products that are exceptionally efficient at lower speed. Part-load efficiency is important for HVAC systems because equipment is sized for a peak load associated with very hot and very cold weather that only occurs for a few hours each year. Also, equipment is often oversized to provide redundancy, which makes the equipment run at even lower part load for most of the year. One study of 259 buildings with hydronic systems found that the equipment was almost always oversized, running at very low load and running more frequently than expected (about 81 percent of the hours of the year for a typical building) [3].

High Efficiency Motor Products

The University of California, Davis (UC Davis) Western Cooling Efficiency Center (WCEC) previously lab-tested five NEMA premium motors as part of the California Energy Product Evaluation Hub. These five motors chosen were representative of commercially available products used in the HVAC industry. The technologies previously lab tested include: traditional induction “squirrel cage” motors, electronically commutated (EC), permanent magnet (PM), switched reluctance, synchronous reluctance (SR), and ferrite-assisted synchronous reluctance motors (FASR).

The two technologies that performed the best at part load were SR and FASR. Both of these motors use magnetic reluctance to produce torque. Magnetic reluctance produces a motor with good power density, high efficiency, and high torque. The ABB EC Titanium product performed the best out of all the motors at part load. The EC Titanium motor is a commercially available but relatively new product (released in 2020) that uses FASR. Thus, the WCEC is exploring this motor in hydronic pumping applications for this project.

Background

As of a 2011 study by the International Energy Agency (IEA), electric motors consume 46 percent of the total power used worldwide [4]. This estimate includes everything from massive 1,000+ horsepower (HP) pumps to small household fans. Since motors consume such a large fraction of total energy demand, even small efficiency gains have significant impacts. For this reason, the Department of Energy (DOE) has mandated a minimum rating of NEMA premium or super premium, depending on the rated HP. The DOE requirements, state-level energy codes, and rising energy costs have led to wider adoption of highly efficient motors.

Motor Technologies

Achieving higher energy efficiency in electric motors has led to the development of many different products. The most common types of motors for central HVAC water pumping applications are induction "squirrel-cage", electronically commutated (EC), permanent magnet (PM), switched reluctance, synchronous reluctance (SR), and ferrite-assisted synchronous reluctance motors (FASR).

Induction motors are sometime called "squirrel-cage" motors because the geometry of the rotor creates a circular cage-like shape. They are simple, rugged, widely available, and have the longest history of commercially available alternating-current (AC) motors. These motors do not require any type of drive to run, and multiple speeds are attained by applying power across different parts of the windings, similar to how a transformer may support multiple voltages. They may also be powered by a variable speed drive for precise speed control. Squirrel-cage motors are typically less efficient than the other types or motors listed here, particularly for variable speed applications. Squirrel-cage motors can be designed to meet NEMA premium efficiency, but super premium is less common.

Electronically commutated (EC) motors, also known as brushless DC motors, can be very lightweight, compact, and are typically more efficient than standard induction motors. They consist of an electronic control module and a three-phase motor with a permanent magnet rotor. Unlike traditional DC motors that use mechanical brushes, ECs use electronic circuits to control the power and speed of the motor, significantly reducing friction and wear. ECs convert single-phase AC power to DC power, which is then pulsed to the motor windings to create a rotating magnetic field. This design allows for precise control of motor speed and torque. EC motors have become more widely used in the HVAC industry, especially for variable speed fans. However, supply chain issues have caused problems in the marketplace, particularly when replacement parts are needed quickly. Also, their low-speed efficiency is lower than that of PM, SR, or FASR motors [6].

Permanent magnet (PM) motors are similar to EC motors in that they both have magnets and require a drive. However, PM motors have different winding design, rotor design, and control than EC motors. The placement of the magnets inside the rotor protects from demagnetization and allows the PM motor to produce both magnetic and reluctance torque, resulting in higher overall torque and efficiency. These benefits apply even at low speed, making PM motors an excellent choice for systems commonly running at part load. However, there are concerns about the cost and climate impact of the rare-earth magnets commonly used in these motors. PM motors also have a high back electromotive force (EMF), with different requirements for variable speed drives, but can be used for regenerative braking [7].

Switched reluctance and synchronous reluctance (SR) motors both take advantage of magnetic reluctance to generate torque. Switched reluctance motors, as the name implies, use a specialized drive to switch stator poles in sequence to produce torque. Some have described them as similar to stepper motors, but with low torque ripple and good application in HVAC, vehicles, and more [8]. Synchronous reluctance motors use a rotor with a variable reluctance core and are driven by a sinusoidal signal. Like their switched cousins, synchronous motors require a special drive, but there are multiple commercially available products. One drawback of these motors is their low power factor [9], [10].

Finally, ***ferrite-assisted synchronous reluctance motors (FASR)*** are the next evolution of synchronous reluctance motors. This technology uses a specially designed rotor core with ferrite magnets inserted into an optimized geometry that improves the saliency ratio. The saliency ratio is the ratio of inductance between aligned and unaligned poles. A high saliency ratio improves the power factor which reduces the size and cost of the drive. The optimized geometry of ferrite magnets increases power density and efficiency. FASR motors are highly efficient at all speeds and partial loads. Their main drawbacks are additional manufacturing cost and the need for a compatible drive. These motors may also be referred to as "SynRM²," "PMa-SynRM," or "PMSM," depending on the source [10], [11].

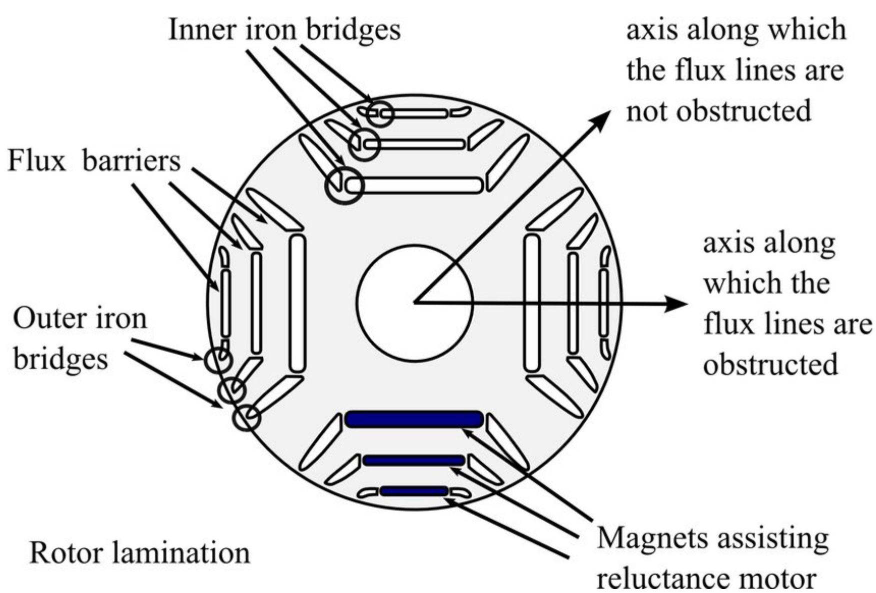

Figure 1: Cross section of a FASR motor rotor core. The core itself is made of laminated steel with flux barriers that improve the saliency ratio. Inserting magnets has several benefits including increased saliency and efficiency.

Source: [8]

Previous Laboratory Results

The WCEC recently tested several motor technologies on a dynamometer as part of the California Energy Product Evaluation Hub (https://energyproductevaluations.org/product_categories/motors/). The goal of this project was to develop guidance for procurement personnel in choosing the correct product for their application to save money and energy. Table 1 shows selected results for five different motors that were all NEMA premium certified. As expected, all motors performed well at their design load. However, the part-load efficiency shows how the more advanced PM, SR, and FASR motors can save a significant amount of energy in variable-speed applications [12].

Table 1: Drive and motor combined system efficiency at different part loads for five highly efficient motors.

Load	Nidec (Induction)	Siemens (Induction)	Marathon Motors (Permanent Magnet)	Turntide (Switched Reluctance)	ABB Baldor EC Titanium (FASR)
100%	86.40%	86.20%	89.50%	91.90%	90.00%
65%	80.40%	80.00%	86.90%	87.40%	88.00%
30%	42.60%	43.00%	62.90%	67.30%	73.00%

Source: [2]

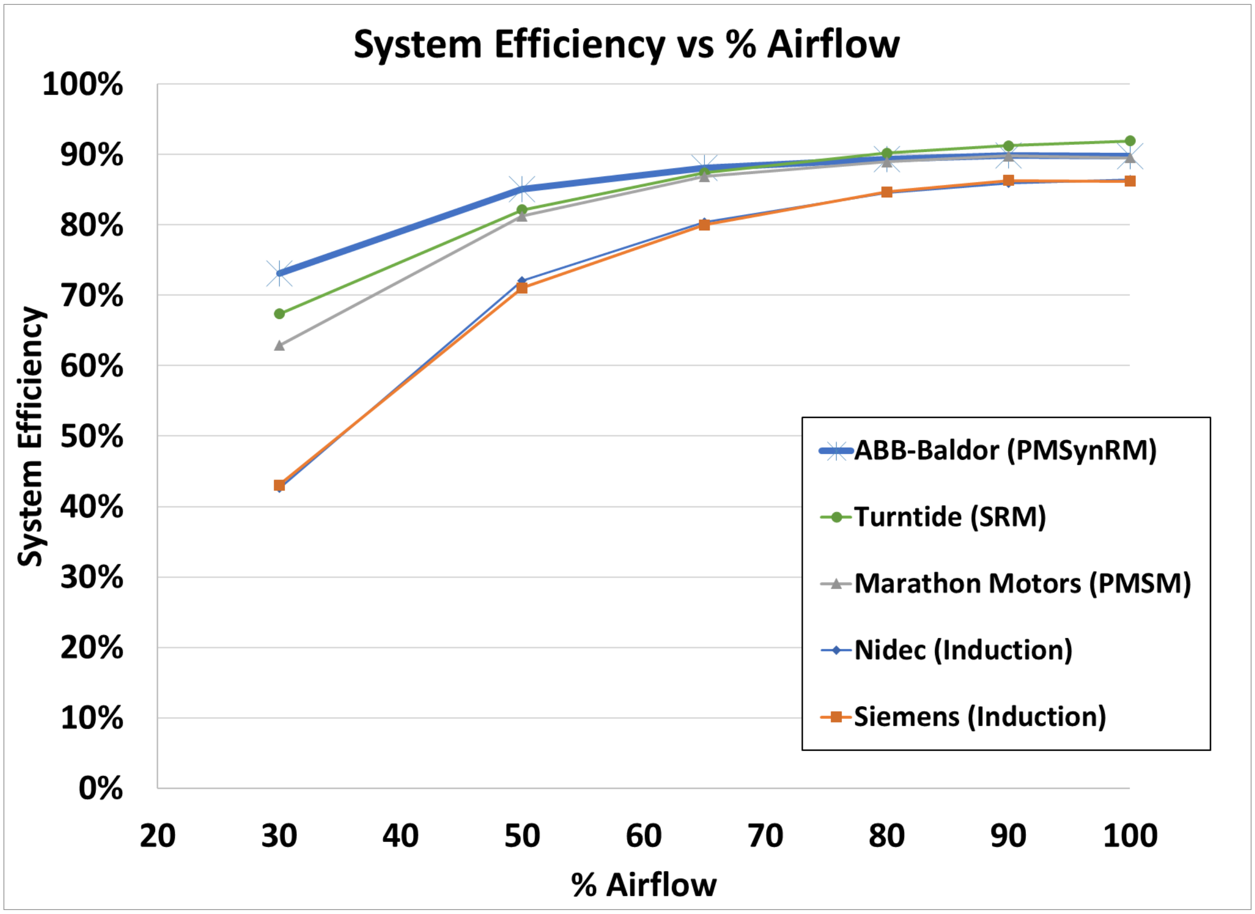

Figure 2: Performance curves for selected motors tested against an airflow profile.

Source: [2]

Previously, WCEC performed EnergyPlus modeling, as well, to estimate savings based on a retrofit case. The model was based on a DOE reference building with roof-top units (RTU) providing heating and cooling to a large retail space. The modeled retrofit was the case where the supply fan motor in the RTU was swapped with one of the tested motors without changing the rest of the system. This modeling was done for all 16 California climate zones and several types of DOE reference buildings. Results showed that annual fan energy savings resulted in a simple payback of about one to five years for the FASR motor, depending on the climate zone and electric utility tariff. Other motors also had good payback, but the especially good performance of the EC Titanium motor at low loads led WCEC to explore this product in further studies and applications.

Motors in Pumping Systems

In the US, pumps account for 25 percent of the total energy used by electric motors, and more than 50 percent in industries that are considered "pumping intensive." [13] In hydronic heating and cooling applications, pumps greater than 5 HP are required by ASHRAE 90.1 and Title 24 to have variable speed controls capable of reducing flow rates to no more than 50 percent of the designed maximum (or the minimum required by the system). Additionally, the standards stipulate that these pumps draw no more than 30 percent of design wattage at 50-percent design flow. A study of 259 buildings with hydronic systems showed that pumps were often running at very low flow rates since equipment must be sized for the highest possible demand. It was also found that equipment was often oversized, even when considering redundancy requirements [3]. Since the equipment is usually running at low flow, there is great potential for energy savings using FASR motors.

Additionally, several case studies reveal insight into energy savings potential. For example, a potable water pumping station in the Netherlands replaced 250 kW pumps with ones that use synchronous reluctance motors. The station has a total of six pumps with storage reservoirs as a buffer. The water demand is usually much higher in warmer months due to the weather and a large influx of tourists to the region, so the variable speed controls and low-speed efficiency of the motors significantly reduced energy consumption. The savings were estimated at 20 percent compared to traditional induction motors, with other benefits such as lower noise and easier controls integration [14].

Another study looked at a 43-floor commercial building in Seattle, Washington that originally used one 20 HP and two 30 HP pumps to supply drinking water. By upgrading to permanent magnet motors, the building was able to reduce to just four 7.5 HP pumps with variable speed drives. The annual pumping energy was reduced by 86 percent, and the property manager incorporated the same strategy in two other large buildings with similar results [15].

Several other studies have shown good energy savings and payback for advanced motors in pumps, fans, and material handling [15]. However, there are no known studies of a FASR motor in a hydronic pump application. Researchers were also interested in a pumping application (as opposed to fans or other equipment) since hydronic pumps are commonly installed in pairs for redundancy and capacity. By pairing the emerging technology product with a baseline motor this project can show a side-by-side comparison in a shorter amount of time.

A simple “two-pipe” hydronic system is shown in Figure 2 where a central chiller is used as needed depending on temperature setpoints. The buffer tank helps provide consistent water temperatures when loads change suddenly, and pumps are used to distribute water to a load, e.g., air handler. The design of a hydronic system can take various forms, but the basic principle of distribution is the same [14]. According to the 2022 California Commercial End Use Survey, hydronic systems account for almost 60 percent of large office building HVAC systems, and 20 percent of all building types by total square footage.

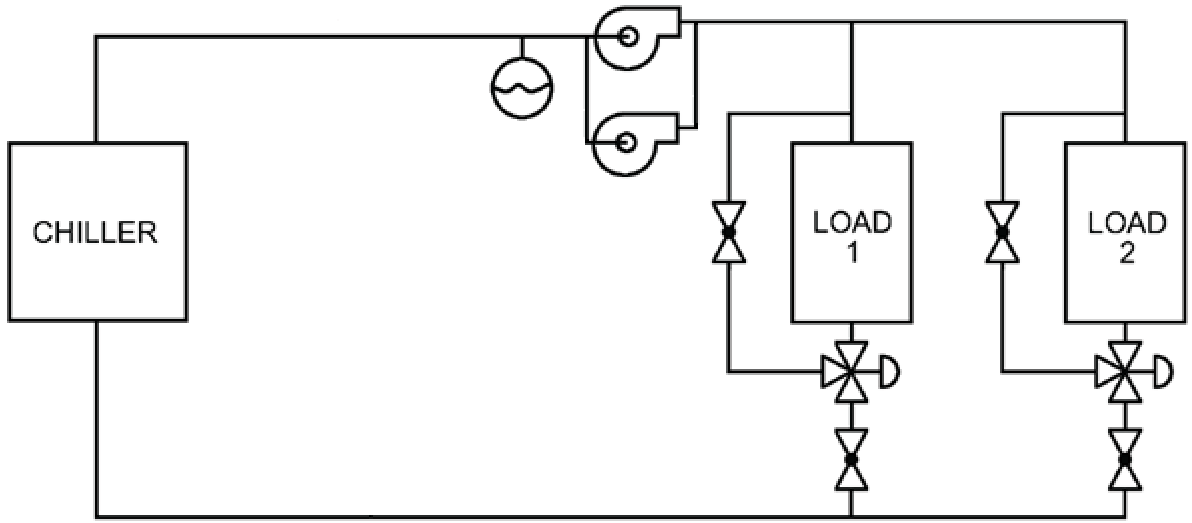

Figure 2: Hydronic system example showing a two-pipe system. Water is cooled as needed by a central plant, and a pump distributes water to loads. In California, the load for cooling is commonly a variable air volume air handler.

Source: [16]

Objectives

The primary purpose of this study was to measure the energy performance of the ABB EC Titanium motor in an occupied building with a hydronic pumping system directly compared to a business-as-usual NEMA premium motor. The steps were to:

- Identify a UC Davis building that is representative of a medium to large office building with a variable air volume (VAV) HVAC system using hydronic reheat at the terminal units.
- Acquire four total replacement pumps and drives: two pumps with ABB EC Titanium motors and two pumps with standard NEMA premium motors.
- During installation, document differences between standard and advanced motors, document any issues, and record solutions to be included in contractor training and design of energy efficiency programs
- Monitor energy consumption of all four motors with drives to predict annual energy savings.
- Analyze data for actual energy savings and demand savings, and to estimate utility bill savings for a typical commercial building.
- Engage in stakeholder outreach to understand market barriers and potential for wider adoption.

- Disseminate the final report to stakeholders and recommend what contractors need to know about the advanced FASR motor type to successfully install them as retrofits.

Methodology and Approach

The UC Davis WCEC team often collaborates with experts from the campus Facilities Management team (hereafter, Facilities) to help with energy savings and understand potential new technology applications. Because of this partnership, we were able to query the entire portfolio of campus buildings to select a site for the pump retrofit with EC Titanium motors. Selection criteria and their relative importance are summarized in Table 2. These attributes align with common large office buildings and their associated HVAC systems in California.

Table 2: Screening attributes for the UC Davis building selection.

Attribute	Preference	Importance
Gross square feet	>20,000	High
Building type	Office	High
HVAC system	VAV with hydronic reheat	High
Number of pumps	2 for chilled water 2 for hot water	High
Pump size	5–7.5 HP	Medium
Labs with high ventilation requirements	None	High

Source: Project team.

Site Selection

We considered more than a dozen buildings for the study. To rule out candidates, WCEC performed visits, reviewed mechanical drawings, and analyzed building management system (BMS) data to determine if the building met the qualifiers in the previous section. Many buildings at UC Davis have labs with high ventilation requirements, which significantly change the energy use intensity and how the HVAC system operates. After careful consideration and many site visits, WCEC chose Dutton Hall, a three-story, 47,459-square-foot administration building constructed in 1998.

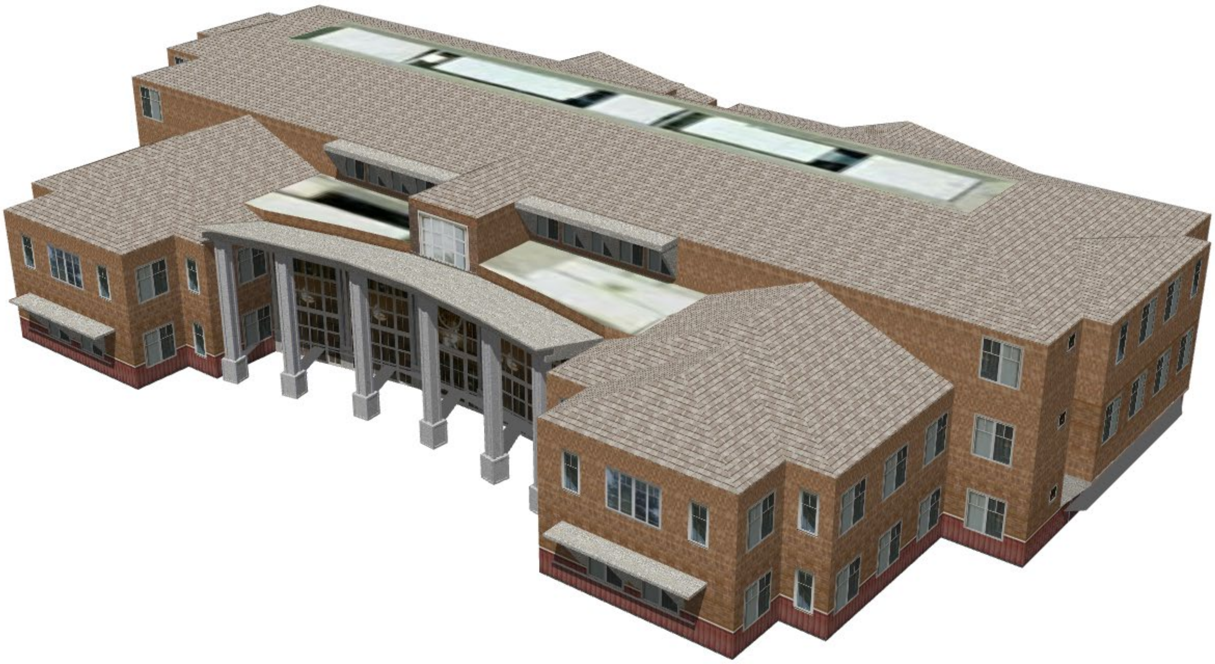

Figure 3: Dutton Hall 3D model

Source: UC Davis Facilities

Dutton Hall is separated into north and south wings and is served with two large air handlers on the roof. Like most California medium or large office buildings, the air handlers have cooling coils but no heat; all heating is performed by hydronic coils at each VAV terminal. There are 67 VAV terminals serving 147 rooms, not including halls and other common spaces. Chilled water (CHW) is pumped from the ground floor mechanical room to the air handlers on the roof using two 7.5 HP Bell and Gossett pumps with variable speed controls. Heating hot water (HHW) is pumped to each of the 67 VAV coils using two, 2-HP Bell and Gossett pumps also on variable speed controls.

Unlike many large office buildings, Dutton Hall connects to the UC Davis district heating and cooling water loops. Building controls were adjusted and monitoring carefully planned to eliminate influence from the district energy system on the building pumps.

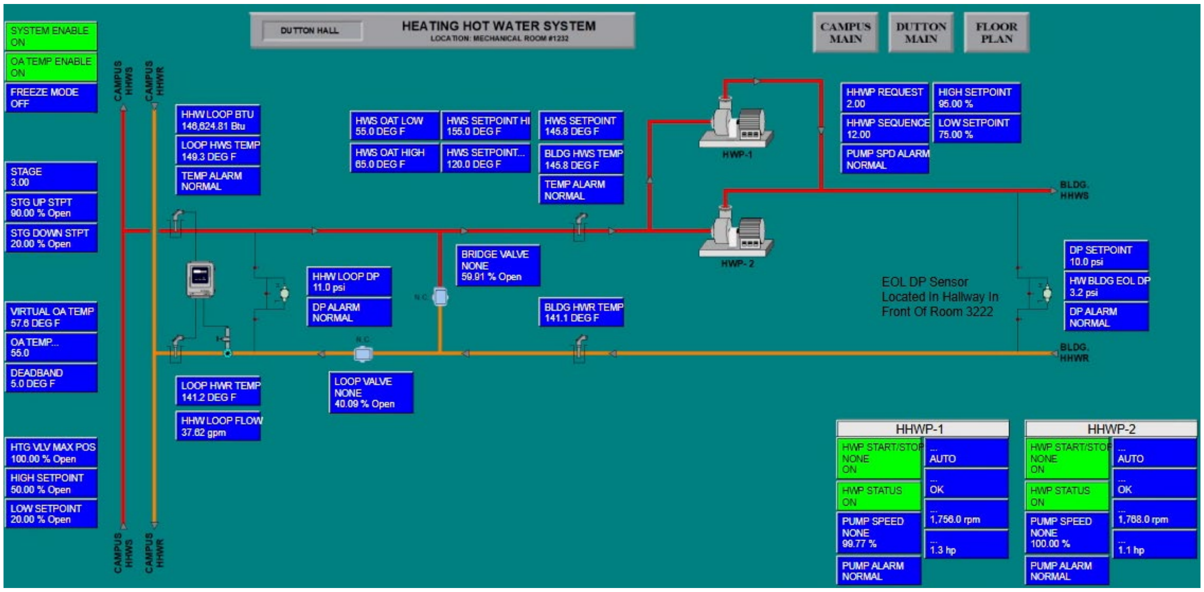

Figure 4: Dutton Hall heating hot water system schematic as shown in the UC Davis BMS system.

Source: Project team

Figure 5: Existing hydronic pumps in the Dutton Hall mechanical room before the retrofit.

Source: Project team

A review of BMS sensors and recorded data showed that most of the sensors needed for the study were in place with reasonable measurements. The HHW end of line differential pressure sensor was broken but quickly replaced when the study team identified the problem. Flow meters have up-to-date calibration certificates.

Data collection used both BMS data and WCEC instrumentation to quantify the energy performance of the pumps. Pressure, temperature, and flow rates are monitored by the BMS system using meter-grade sensors. WCEC verified BTU meters with their respective temperature and flow sensors had up-to-date calibrations. End-of-line pressure sensors were checked with a handheld pressure gauge. Additional pressure sensors and energy meters were installed to monitor the pumps directly. The monitoring period included heating season, shoulder season, and cooling season data to enable estimation of annual energy savings.

Table 3: Measurement Points

Measurement Point	Source	Make and Model	Uncertainty
District hot water flow	BMS	Onicon F3500-11-C3-1211 electromagnetic flow meter	± 1% of measured value for flow 2-20 ft/s
District cold water flow	BMS	Flexim Fluxus	± 1% of measured value
End of line differential pressure	BMS	Setra 231	± 1% full scale
Hot water temperature (supply and return)	BMS	Onicon F3500-11-C3-1211 electromagnetic flow meter	± 1% of measured value
Cold water temperature (supply and return)	BMS	Flexim Fluxus	± 1% of measured value
Pump pressure rise (4 Pumps)	WCEC Instrumentation	Dwyer 645-5	± 0.25% full scale ± 0.02% full scale/°F
VFD power input (4 VFDs)	WCEC Instrumentation	Dent PowerScout 3+	Power meter: 0.2% (<0.1% typical) Current transducer: <0.5%

Source: Sensor and data acquisition equipment specifications

The project team installed sensors connected to a Datataker DT85 with 1 minute logging intervals and hourly uploads. The BMS data was logged at 15-minute intervals and aggregated in a database maintained by UC Davis Facilities. Figure 6 is a schematic of the relevant sensors monitoring the pump systems. Although CHW and HHW loops are separate, this figure is representative of both systems.

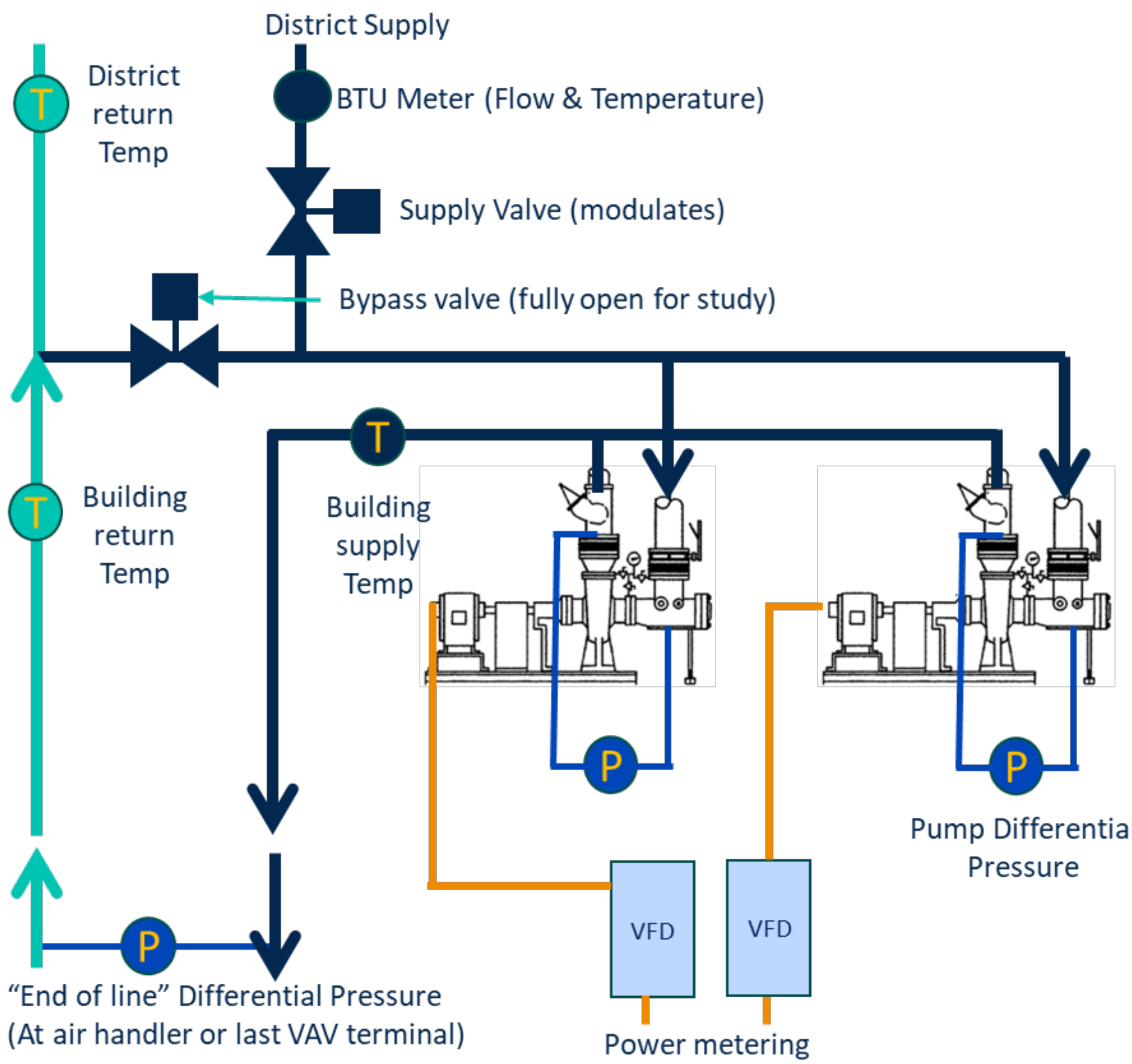

Figure 6: Pump and sensor location schematic. Representative of both chilled water and heating hot water systems.

The team worked with a representative of the Bell and Gosset pump distributor who is integrating the EC Titanium electric motors with the pump heads on standard mounting rails for drop-in replacement.

We specified, ordered, received, installed, and commissioned replacement motor integrated pumps and VFDs. The new pumps were designed to be a like-for-like swap to avoid unnecessary plumbing work. The research team held multiple meetings with the UC Davis Facilities controls group, electrical shop, and plumbing shop to coordinate and observe installation. The VFDs were installed first while the pumps and motors were assembled and shipped.

For energy measurement and verification, we ran the baseline and EC Titanium motors in parallel at the same speed and connected to the same return water manifold and supply water manifold. The motors ran on the same schedule and speed setting so that the team could directly compare their efficiency under the same operating conditions. The building heating hot water and chilled water district supply valves were controlled to meet a supply water temperature, while the bypass valve was kept completely open to eliminate any effects from district loop pressures. We verified successful isolation by measuring that the pressure difference across the pumps was zero when the pumps were turned off, indicating that there was no flow driven by the campus loop. Also, when the pumps were operated in parallel, the comparison of electric motor efficiency would not have been significantly influenced even if there were problems in the isolation of the building from the district energy system water loops.

In parallel operation, we measured the differential pressure across each individual pump head and used the differential pressures and manufacturer pump curves to calculate the flow rate of water from each individual pump.

Findings

This section presents findings for the process of procurement and installation in addition to the quantifiable energy savings. We describe the availability of the product, ease of installation, and control strategy. The energy savings and notes on performance are separated by heating hot water (HHW) and chilled water (CHW) system. The team calculated simple payback with an assumed electricity cost.

Procurement

The existing pumps were Bell and Gossett E-1510 end-suction pumps, two for HHW and two for CHW. With input from UC Davis Facilities, a like-for-like replacement was ordered. Pump specifications were taken from nameplate data and building mechanical plans and are summarized in Table 4. We found that the manufacturer had kept pump design consistent for many years, so university staff commonly re-ordered the same pumps for drop-in replacement without needing to be concerned about dimensional changes. In fact, newer high-efficiency motors can be installed without disturbing the existing impeller. For this project, the team selected a whole pump or “skid” replacement, since the performance of the existing equipment may have degraded over time.

Table 4: Details of the four hydronic pumps ordered.

Pump	Model	Impeller	Head	Flow	HP	Motor	Price
HHW-1	B&G E-1510 1.25 BC, SS	8.75 in	82 ft	36 GPM	2	ABB Baldor Super-E	$5,278.18
HHW-2	B&G E-1510 1.25 BC, SS	8.75 in	82 ft	36 GPM	2	ABB Baldor EC Titanium	$5,521.82

Pump	Model	Impeller	Head	Flow	HP	Motor	Price
CHW-1	B&G E-1510 2.5 BB, SS	8.75 in	75 ft	171 GPM	7.5	ABB Baldor Super-E	$7,301.82
CHW-2	B&G E-1510 2.5 BB, SS	8.75 in	75 ft	171 GPM	7.5	ABB Baldor EC Titanium	$6,898.18

The pumps were ordered from a local distributor that covers multiple hydronic equipment brands and offers installation, commissioning, and engineering services. Their team provided good feedback and had no issue configuring the pumps with the requested motors. The total before taxes was exactly $25,000. The price increase for the advanced motor was $243 for the 2-HP motor and $403 for 7.5-HP. Lead time was quoted at four weeks but there was a delay of two weeks due to backlogged production at the pump manufacturer. The UC Davis Facilities team was fully booked for eight weeks, so pumps were on-hand for the scheduled installation window.

In addition to the pumps, new VFDs were ordered since the existing models, ABB ACH-550, were not compatible with the FASR motor type. The previous model ABB VFD, ACH-550, was discontinued at the end of 2019 and the current model ABB sells is the ACH-580. It is unclear how many brands support FASR motors, but the ABB ACH-580 comes with preconfigured options specifically for their EC Titanium motors. Also, ABB is the preferred VFD brand for UC Davis Facilities. These drives were in stock and came to a total price of $4,272.00. The EC Titanium motors can come with integrated drives for less than the price of the separate motor and a new ACH-580, but the external drive option was preferred by facilities since it allows more flexibility. In general, facilities indicated that VFDs are not replaced if they are still working and compatible with the new motor. Occasionally, if the budget allows, a working VFD will be replaced if it allows for better control and energy efficiency.

Installation and Commissioning

Installation was coordinated between UC Davis facilities across three skilled trades, pipe fitters, electricians, and controls engineers. The feedback from the initial installation was that the installation was routine work; the high efficiency motor did not require additional time or materials. Since the electrician was tasked with VFD startup, their workflow was the most affected by the new motor type. However, this change was minimal. Only three parameters are different from the startup of a traditional induction motor: 1) Nominal voltage is not supply voltage, it is the nameplate back-EMF. 2) Control type is “vector” rather than scalar. 3) Motor type is “PaSynRM” (or “EC Titanium” on newer firmware versions). The billed time for each trade is shown in Table 5. This includes some hours billed for adjustments required to enable comparisons for this test and to fix issues unrelated to the motors themselves. The facilities team estimated that a typical total pump and VFD replacement would take 24 person hours, which includes two plumbers, one electrician, and one controls engineer.

Table 5: Breakdown of trades and billed hours for the project.

Trade	Task	Hours	Note
Plumbing	Pump and motor physical installation	24	Additional time for impeller resizing and replacing flow straighteners (issues unrelated to motors).
Electrical	Wiring and VFD startup	30	One-hour line item specifically mentions research on EC Titanium motor. The 30-hour figure includes hours billed to move VFDs to a more convenient location. This would not be necessary in typical retrofits and was not a separate line item.
Controls	Setpoints and VFD communication to BMS system	18	Includes time to change and test controls to run pumps in parallel instead of lead lag. This would not be part of a typical retrofit.

Heating pumps were commissioned first to prioritize data collection during winter and early spring. Several issues unrelated to the motor itself were identified. First, the end-of-line differential pressure sensor was broken, causing pumps to always operate at 100 percent. This was fixed by Facilities using parts they had on-hand. The second issue was more involved. The original HHW pump impellers were trimmed to a smaller size (7.625”) due to low head and high flow rates causing motors to overload. However, this change was never documented, so the new pumps were ordered based on the original nameplates. When the new pumps were installed, the motors began to overload again. The impeller issue was discovered by measuring RPM and pressure versus the old pumps and using the manufacturer's data sheets. The data from the original pumps did not match the data sheets, so one was disassembled to check for restrictions. No restrictions were found, but the difference in impeller diameter was obvious so the new impellers were machined to match. Impeller trim is common practice and fixed the issue but did cause a 2-week delay. Afterwards, the chilled water pumps were commissioned without incident.

The team configured controls to run the pumps in parallel for direct comparison between operating points. The building management system controlled the speed of both pumps with a proportional integral (PI) control loop with an end-of-line differential pressure (EOLDP) setpoint. The EOLDP was set to 10 psi for hot water, and 8 psi for chilled water. To avoid supply water circulation from the difference in pressures between the district supply and return loops, the district side bypass valve was kept fully open and the district-to-building supply valve modulated to reach the target supply water temperature.

Figure 7: Four pumps after final installation. The manufacturer painted all motors red as is typical for their products.

Energy Monitoring Results

Parallel Operation: Heating Hot Water

The HHW pumps ran continuously during occupied hours at an average of 78 percent of full speed. Figure 8 shows the distribution of operating speed. Although both pumps received the same control signal, the baseline pump runs at a lower RPM because it is not a synchronous motor and therefore experiences slip. Measurements show that a control signal of 78 percent will cause the baseline induction motor to spin at 1,375 RPM, while the EC Titanium spins at a synchronous speed of 1,404 RPM. For these pumps, the difference in speeds is not an issue for building operation but should be noted in applications where motor speed is more critical.

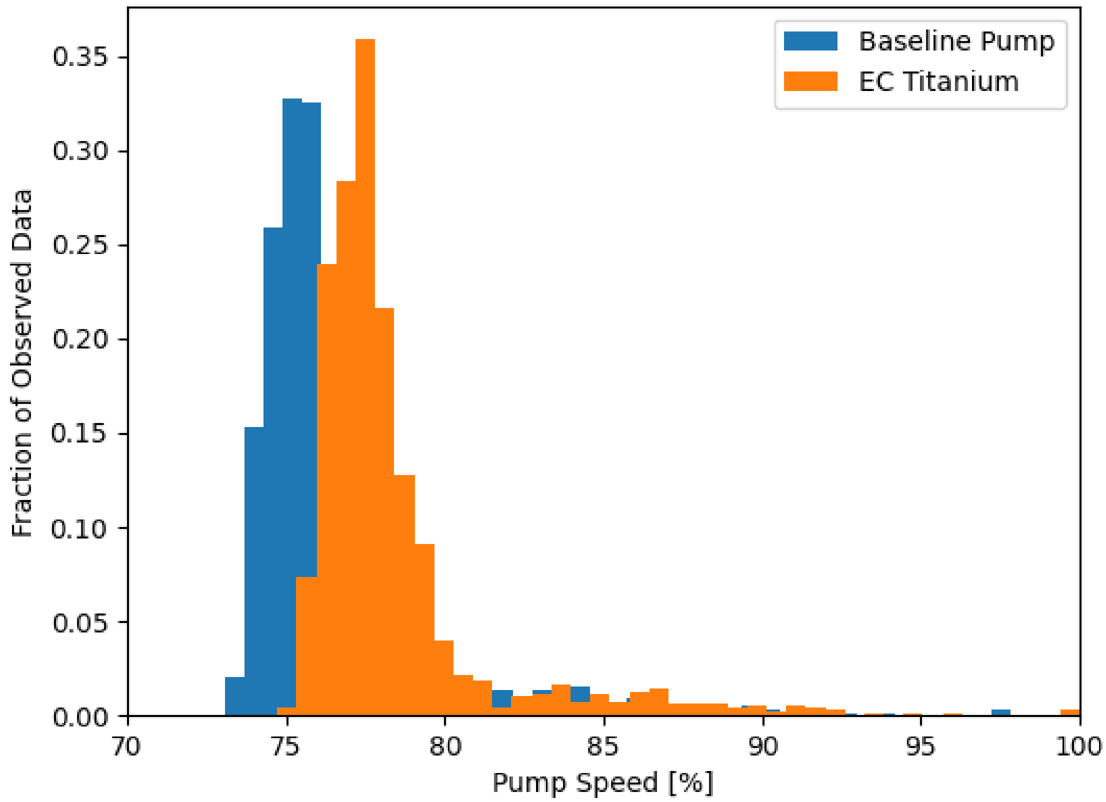

Figure 8: Heating hot water pump speed distribution, for parallel operation with both pumps running simultaneously.

Figure 9 shows HHW pump power in steady state versus different building load bins during operating hours. The HHW system is programmed to turn off outside of the building operating hours schedule and when there is no call for reheat, however during occupied hours there is always at least one VAV unit requesting heat, due to zones with little internal heat generation to balance the cooling provided by the required minimum ventilation air flow rates. One room on the bottom floor facing east with trees providing full exterior shade was observed to require reheat most of the time. The bottom floor common area also frequently required reheat.

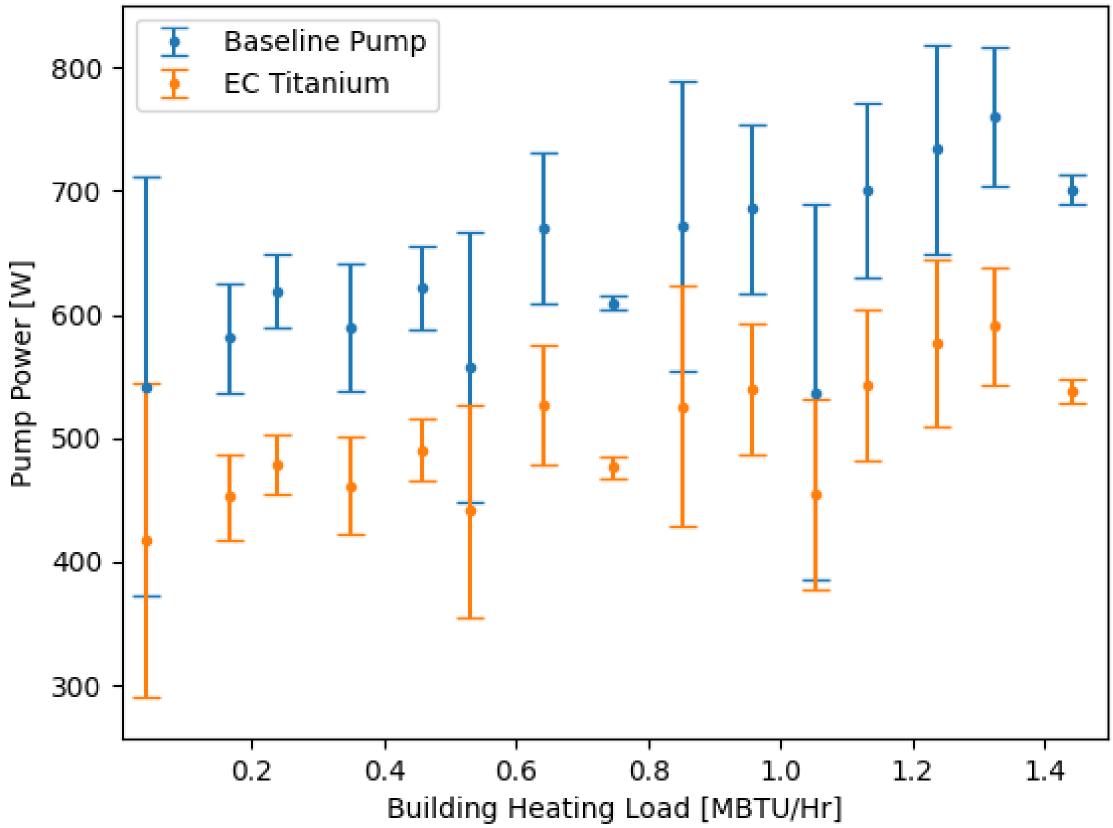

Figure 9: Heating hot water pump power versus outdoor air temperature during operating hours, for parallel operation with both pumps running simultaneously. Bars indicate the standard deviation of observed data. Data is filtered for steady state operation.

Asynchronous motors, including the baseline induction motor in this study, have slip that results in slightly lower achieved RPM for a given speed input than a synchronous motor technology such as the PaSynRM EC Titanium motor. The slightly lower RPM due to slip for the baseline induction motor means that it is pumping water at a slightly slower flow rate compared to the EC Titanium motor. For the baseline motor to pump water at the same flow rate, it would need to operate at the same RPM, and it would consume more power to do so. To make direct comparison, the total system hydraulic efficiency is calculated across the individual pump flow rates so the baseline and upgrade can be compared. The total system hydraulic efficiency is defined as the flow power of delivered divided by the input electrical power supplied to the VFD:

$$\eta = \frac{dP * GPM * 0.1886}{P_{in}}$$

where the total system hydraulic efficiency (η) is the differential pressure (dP) in feet of water column times the flow in gallons per minute (GPM) times a unit conversion factor of 0.1886 to obtain Watts in the numerator. P_{in} is the measured electrical power consumed in Watts.

In this study, power monitoring is placed before the VFD, so the electric motor efficiency, pump head hydraulic efficiency, and the VFD efficiency are included in the total hydronic system efficiency shown in Figure 10 with data filtered for steady state operation. This shows the significantly higher efficiency for the EC Titanium motor compared to the baseline. At the most common speed of 78 percent, the FASR motor consumes 12 percent less power than the baseline NEEMA premium induction motor.

Table 6 summarizes the energy savings for the hot water pump system. A simple payback calculation is also presented, using the average $0.39 rate for PG&E commercial A-10 service. The payback calculation is based on a scenario in which the motor is already scheduled for replacement and the cost is the difference between the baseline motor and the emerging technology. This case fits with new construction, retrofits where the existing VFD was broken or old enough to be replaced even for a baseline motor, and for retrofits where the existing VFD was the newer model and did not need to be replaced. An additional retrofit scenario is considered where the existing VFD is relatively new, with a significant remaining expected useful life, but does not support FASR motors so it must be replaced only for the advanced motor and not for the baseline motor. In this scenario, the cost of the VFD equipment and potentially the cost of the VFD installation must be paid back by energy cost savings. Because VFD installation costs can vary widely between sites, the second payback calculation in Table 6 below only includes the equipment cost premium for the motor and the full equipment cost for the VFD. It should be noted that the VFD cost is based on a stand-alone drive, which costs more than the integrated drive. This means that there may be opportunities for faster paybacks for sites that need to replace existing VFDs and select EC Titanium motors with integrated drives.

Table 6: Energy savings and payback for the heating hot water system.

	Energy Used	Energy Saved	Payback (motor only)[1]	Payback (motor and VFD equipment)[2]
Baseline motor	13.5 kWh/day	-	-	-
EC Titanium	11.1 kWh/day	18% (2.4kWh/day)	0.34 years	3.3 years

[1] Payback includes the cost difference between NEEMA premium induction motor and the EC Titanium FASR motor using the average $0.39 rate for PG&E commercial A-10 service.
[2] Payback includes motor cost premium and full cost of VFD equipment; it does not include VFD installation cost.

Figure 10 below shows that because the HHW pumps run at relatively high speed, as the speed increases, the pump head hydraulic efficiency decreases faster than the motor and VFD efficiency increases for a net reduction in total efficiency.

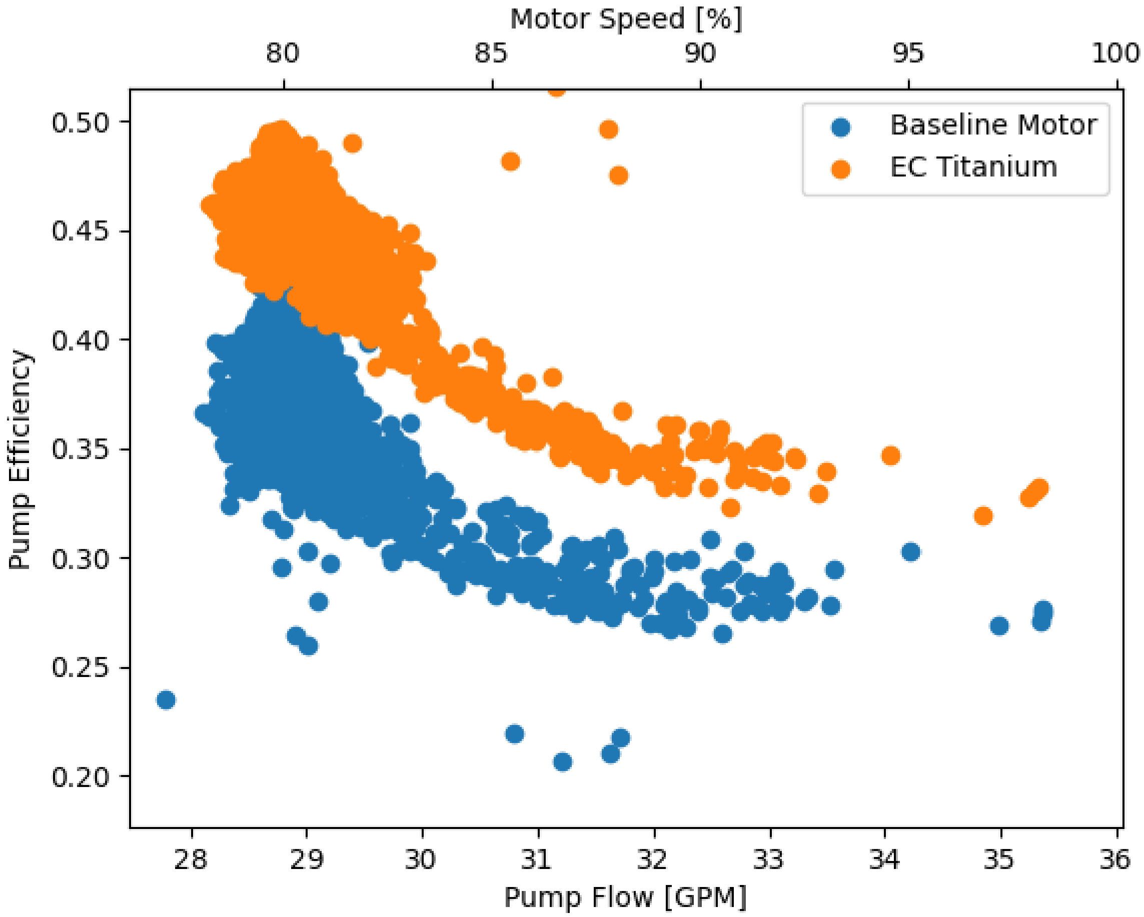

Figure 10: Heating hot water hydronic pump system efficiency versus flow rate, filtered for steady state operation.

The small RPM difference caused by baseline asynchronous motor slip leads to small differences in flow rate. For these small differences pump affinity laws can be used to accurately predict the adjusted electrical power that the baseline motor would consume if it had no slip and ran at the same RPM as the FASR motor. Pump affinity laws show that the flow power increases as the third power of the ratio of adjusted flow rate divided by measured flow rate. Even though the RPM and flow rate differences are small, the third power dependence amplifies the differences in power and energy to be significant. Adding up the adjusted HHW baseline motor power for each time step over the monitoring period results in 28 percent energy savings. The adjusted energy savings and payback times are shown in Table 7.

Table 7: Adjusted energy savings and payback for the HHW system.

	Energy Used	Adjusted Energy Saved (no baseline motor slip)	Payback (motor only)[1]	Payback (motor and VFD equipment)[2]
Baseline motor	14.6 kWh/day	-	-	-
EC Titanium	11.1 kWh/day	28% (3.46 kWh/day)	0.25 years	2.4 years

[1] Payback includes cost premium difference between NEEMA premium induction motor and the EC Titanium FASR motor using the average $0.39 rate for PG&E commercial A-10 service

[2] Payback includes motor cost premium and full cost of VFD equipment, does not include VFD installation cost

Parallel Operation: Chilled Water

CHW pumps were larger (7.5 HP) but consumed less power than the HHW system. The BMS requested low to moderate speeds, between 20 and 50 percent, to meet the end-of-line pressure setpoint. The rooftop air handlers are equipped with two-way modulating valves (no bypass) and were observed to modulate between 0 and 70 percent, with one unit never requiring above 35 percent. The air handler coils were designed for 46°F entering water and 50°F supply air but are currently set to 40°F water and 64°F supply air.

Figure 11 shows power use versus building load for the chilled water system filtered for steady state operation. This plot demonstrates the low power use and energy savings for the EC Titanium motor. The pump power is relatively flat at the low operating points observed in the data, which matches the manufacturer's performance curve. This is due to the increasing efficiency of the pump head impeller, electric motor, and VFD as the speed increases from very low to low speeds, mostly offsetting the increase in hydraulic power supplied to the water so that power consumption remains flat.

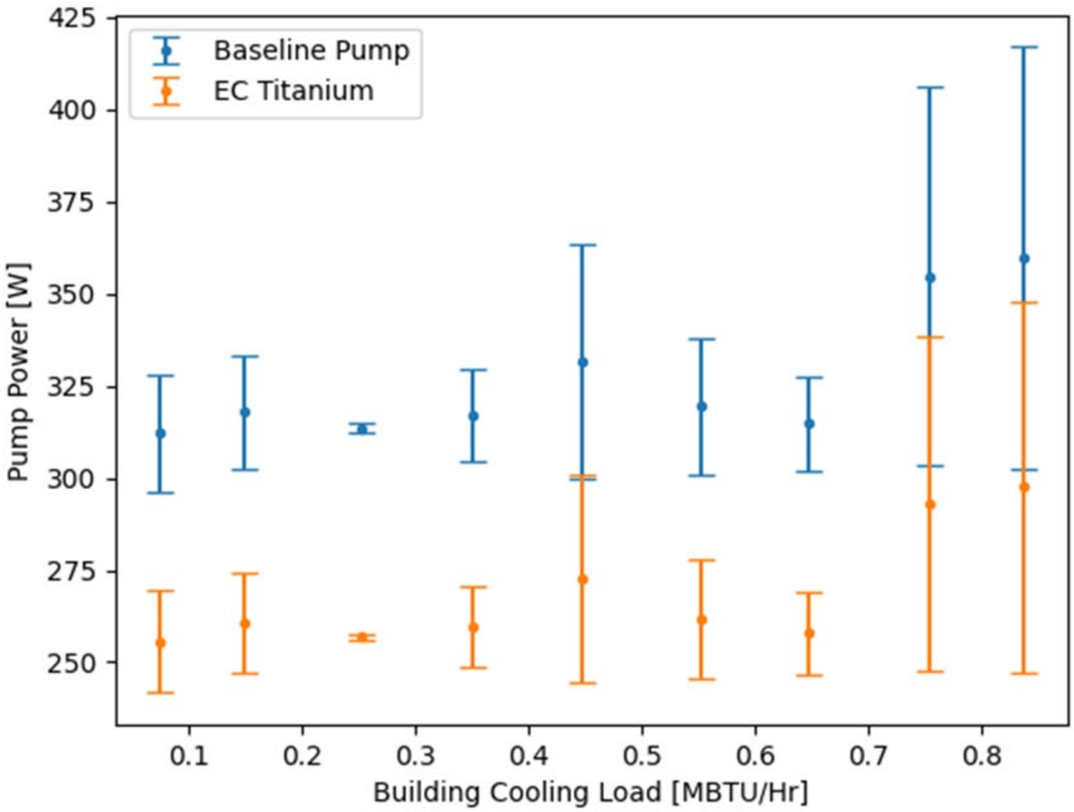

Figure 11: Chilled water pump power versus building cooling load, filtered for steady state operation.

The CHW system baseline induction motors experienced the expected slip. As a result, the EC Titanium motor pumped more water than it would have if it was possible for the motors to operate at exactly the same RPM. As in the HHW results, direct comparison is made possible by plotting total system hydraulic efficiency versus flow for each pump system. The total hydronic system efficiency for both motors is low due to very low to low speed operation. Figure 12 shows the distribution of system efficiency versus flow rate. When pump speeds increase from very low to moderate, both the pump hydraulic efficiency and the motor and drive electric efficiency increase, so the total hydronic system efficiency increases. The FASR was 25 percent more efficient at the highest observed load and converges with the baseline at very low loads. The points near 40 GPM represent only 5 percent of the rated power. Table 8 shows the energy savings and payback for the CHW motor. Total energy per day is more than the HHW system since the CHW flows are higher and it is currently running 24 hours a day.

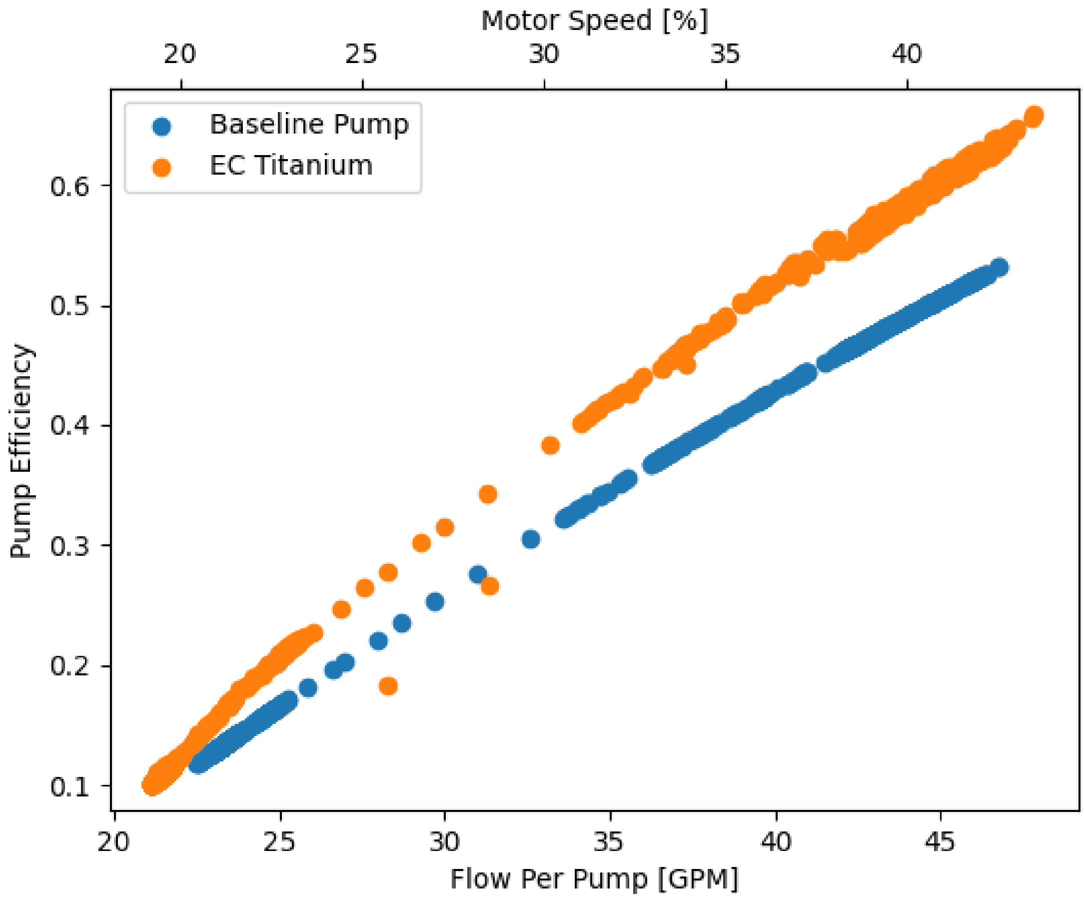

Figure 12: Chilled water pump efficiency at different flow rates.

Table 8: Chilled water pump energy savings and payback.

	Energy Used	Energy Saved	Payback (motor only)[1]	Payback (motor and VFD)[2]
Baseline motor	26.7 kWh/day	-	-	-
EC Titanium	25.3 kWh/day	17.9% (2.2 kWh/day)	2 years	5 years

[1] Payback includes cost premium difference between NEEMA premium induction motor and the EC Titanium FASR motor using the average $0.39 rate for PG&E commercial A-10 service.
[2] Payback includes motor cost premium and full cost of VFD equipment; it does not include VFD installation cost.

Adjusting the baseline power and energy consumption to correct for slip in the baseline induction motor results in 21.9% CHW adjusted energy savings. The adjusted energy savings and payback times are shown in Table 9

Table 9: Adjusted chilled water pump energy savings and payback.

	Energy Used	Adjusted Energy Saved (no baseline motor slip)	Payback (motor only)[1]	Payback (motor and VFD equipment)[2]
Baseline motor	35.7 kWh/day	-	-	-
EC Titanium	25.3 kWh/day	21.9% (2.22 kWh/day)	1.3 years	4.4 years

[1] Payback includes cost premium difference between NEEMA premium induction motor and the EC Titanium FASR motor using the average $0.39 rate for PG&E commercial A-10 service.
[2] Payback includes motor cost premium and full cost of VFD equipment; it does not include VFD installation cost.

Lead-Lag Operation: Heating Hot Water

To expand the range of pump speeds in the monitoring data, the pumps were switched to lead-lag operation where one pump is activated alone until it reaches a specified speed threshold and then both pumps are activated. The data shown here is during the cooling season for single pump operation. In this mode of operation, the power consumption of the baseline and FASR motor cannot be directly compared because they would be operating at different head pressure depending on the number of HHW valves open at the time. The system total pumping efficiency includes the head pressure effect and can be compared as long as the difference in head pressure between the pumps is small, Figure 13. In this data the baseline and FASR pumps are operated separately with the measured water flow rate coming from only the active pump, so the efficiency for each water flow rate can be compared directly without adjusting for slip in the baseline motor.

In the cooling season, the heating hot water pump operates at a lower flow rate than measured previously, but still with relatively high head pressure due to the EOLDP setpoint, reducing pumping efficiency for baseline and FASR.

For heating hot water pumping, there are a relatively small number of zones that regularly call for reheat, so the head pressure stays within a relatively narrow band, and the measured efficiency point clouds do not overlap significantly. There is a clear efficiency advantage for the FASR motor over the baseline induction motor. Due to the narrow range of head pressure during the single pump operation period, a rough comparison of energy consumption shows that the EC Titanium motor saved 1.8 kWh per day on a time-weighted average. This is less than the previous parallel operation period due to the lower hot water flow rates in cooling season, but still a 24.7% electrical energy savings.

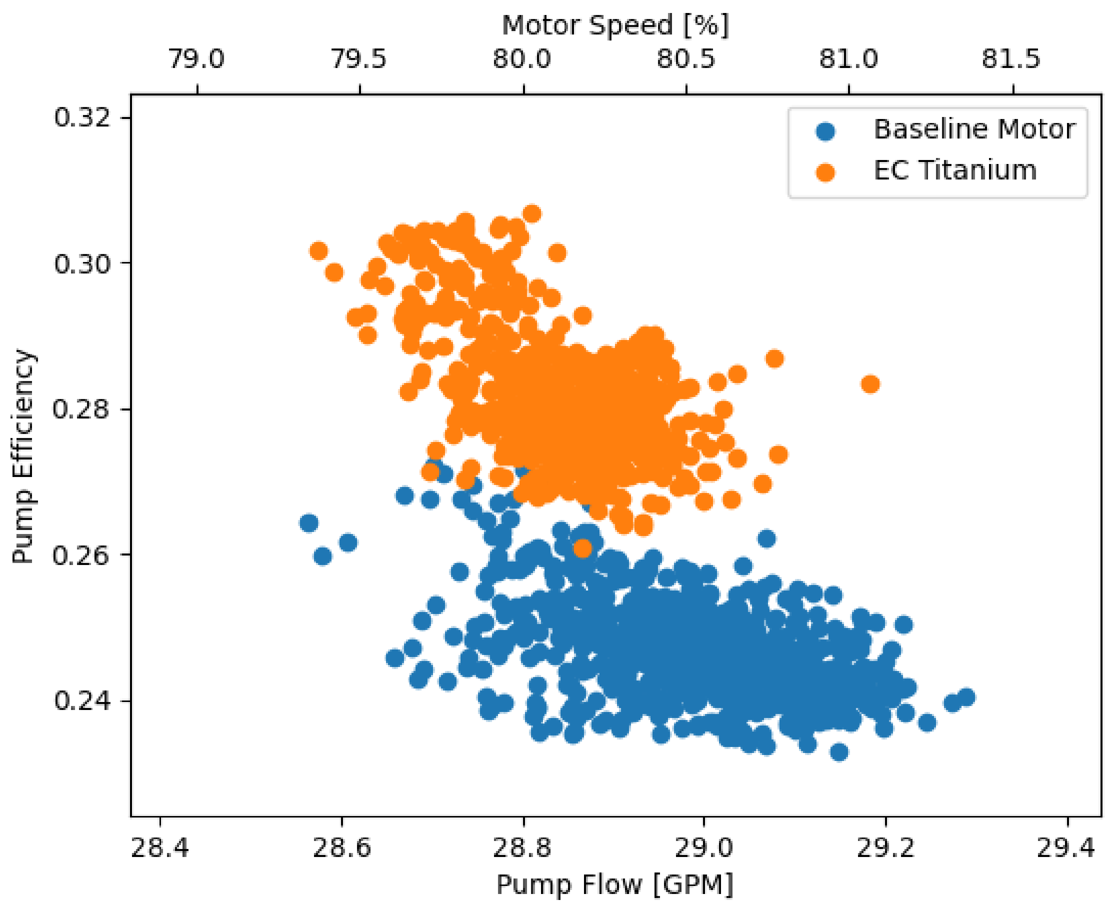

Figure 13 Heating hot water pump efficiency versus flow rate, one pump at a time. The steady state operating points lie in a narrow band due to consistent low heating demand during cooling season.

Lead-Lag Operation: Chilled Water

During lead-lag control operation with a single chilled water pump active, the modulation of the two AHU chilled water valves causes significant variation in system head pressure. This fluctuation leads to changes in pump efficiency, resulting in overlapping performance data for the two motors. Figure 14 shows the pump performance data filtered for periods where the pressure to flow correlation was calibrated. Across these operating states there is a clear efficiency advantage for the FASR motor over the baseline induction motor. The electrical energy savings per day was 1.8 kWh on average. This energy savings is an underestimate because the FASR motor operating period experienced generally higher loads with an average pressure rise 15% greater than the baseline motor.

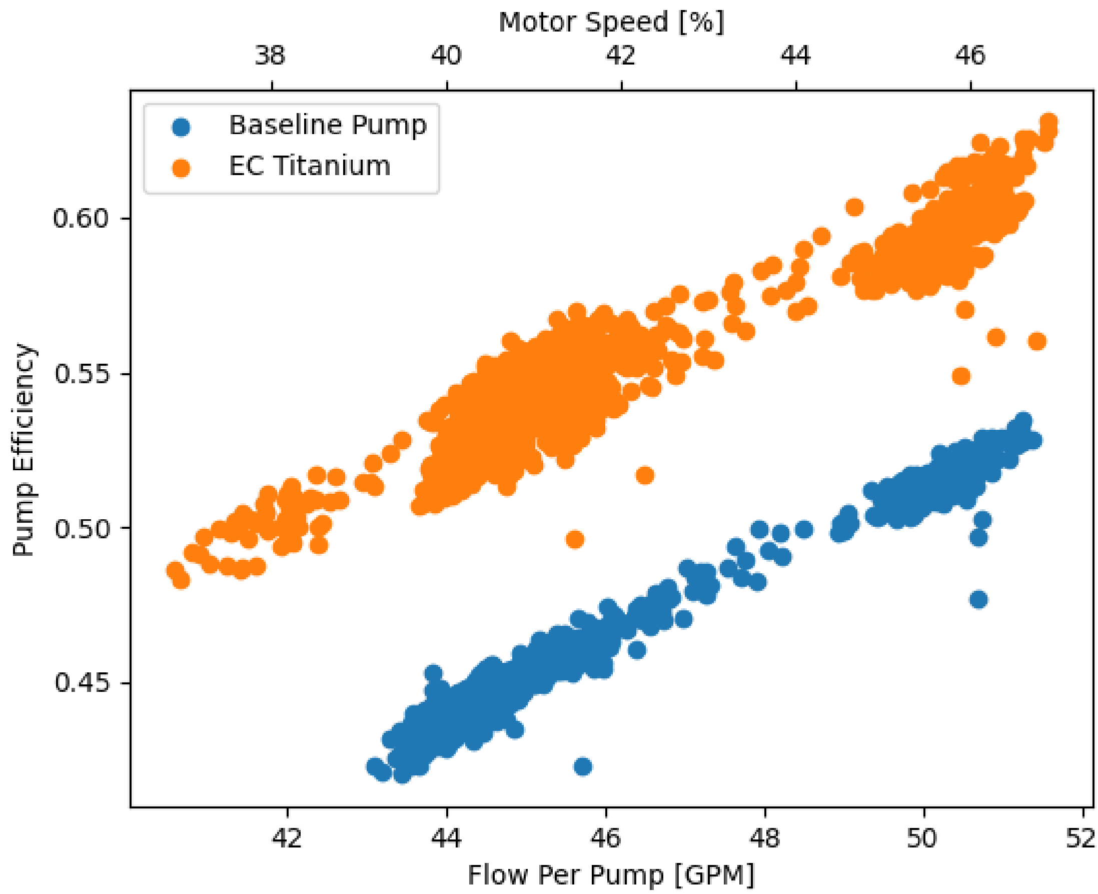

Figure 14: Chilled water pump efficiency and flow rate with one pump at a time, steady state operation filtered for periods where the pressure to flow correlation was calibrated.

Stakeholder Engagement

UC Davis Facilities

Various teams from UC Davis Facilities Management have been involved in the building selection process, project execution planning, and measurement and verification. Overall, feedback has been positive. Like-for-like replaceability for the new motors and VFDs has helped to mitigate concerns about using the EC Titanium motors technology for the first time. Availability of the motors from known distribution channels and the ability to order the motors paired with a variety of pump heads have also increased confidence for the Facilities teams.

Feedback from the plumbing trade experts was that the new motor did not change their usual routine. It complies with industry standard mounting and was not noticeably heavier. No lifting equipment or other special tools were needed for the installation. Their overall conclusion was that they would be open to adopting the emerging technology and were happy it did not require new training or tools.

As noted in the Installation and Commissioning section, the electrical shop experienced the largest change to their usual routine. However, they did not require special training and were happy the drive was already one they commonly use on campus. The electrician was excited to see the motor installed and asked about other applications.

Energy Solutions Advanced Motors Focus Pilot Team

The project team shared experience from this project and previous projects with the Energy Solutions Focused Pilot Advanced Motors project team, including observed questions from facilities stakeholders, previous test results, and lessons learned in previous VFD installations.

Pump and Motor Distributors

We engaged several distributors of advanced motors during the procurement process. While they were generally unaware of the energy and cost savings potential, they were knowledgeable about the technical aspects of the products and were able to provide the necessary technical guidance to order the correct materials for the project. The team worked with the Bell and Gosset pump distributor California Hydronics to custom-order the EC Titanium electric motors integrated with the pump heads on standard mounting rails for drop-in replacement. The team will continue to engage with the distributors to encourage them to offer the high efficiency EC Titanium motors as a standard product offering.

Efficiency Program Implementers

The project team discussed the FASR electric motor technology with Wildan, a third-party utility energy efficiency program implementer. Wildan provided feedback that this could potentially become a rapidly installable efficiency measure for HVAC hydronic pumping. They also mentioned that this measure could potentially be delivered through deemed, custom, or normalized metered energy consumption pathways.

California Technical Forum

The project team met with representatives from the California Technical Forum (CalTF) to present initial findings and inquire about pathways towards measure implementation. CalTF was receptive and noted that the savings were significant and provided information on existing measures that could be modified to include the emerging technology. The project team will follow up with CalTF and contact additional individuals who work on measure development for motors and HVAC.

Recommendations

This project demonstrated that manufacturer claims and previous lab testing of EC Titanium FASR motors translate into real-life savings. Four hydronic pumps were replaced in a UC Davis building with side-by-side comparison of pumping efficiency. The emerging technology saved 18 to 20 percent of measured energy and adjustments to correct for differences in motor RPM predict savings of 22 to 28 percent of adjusted energy. Installation costs were very similar to the baseline motors, except for the potential additional cost of replacing the VFD if necessary.

Given the strong performance of the EC Titanium motors in this field evaluation, the project team recommends that existing efficiency measures be updated, or new measures created to accelerate adoption of ferrite-assisted synchronous reluctance (FASR) motor technology. The combination of significant energy savings, potential for relatively short payback periods, and straightforward installation makes this an attractive option for new construction and replace-on-burn-out retrofits that will not need to replace the VFD.

The existing deemed measure SWHC008 covers conversion from single-speed chilled water pump motors to variable speed with VFD. SWHC008 does not have any recent claims, likely because variable speed drives are now required by code for this application. Updating SWHC008 to include both VFD and an advanced electric motor that is above code requirements is one potential way to revive this measure for existing efficiency programs.

Additionally, it would be beneficial to develop procurement guidance and contractor training materials, particularly around VFD compatibility and configuration.

Next Steps

The next steps for future projects are:

- Continue to engage with measure development partners for more stakeholder feedback and next steps.
- Develop EnergyPlus simulations using lab-measured electric motor performance curves to estimate energy savings in different types of commercial buildings across California climate zones.
- Examine barriers to adoption, especially potential issues with VFD configuration. Test if VFDs have built-in fault detection if configured incorrectly for the new motor type.
- Conduct a detailed market study to identify VFD compatibility and cost information for FASR and other PaSynRM motors from ABB, WEG, and any other manufacturers.
- Determine if lab-measured electric motor performance data can supplement or replace incomplete data or assumptions in existing efficiency measures.

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