August 29, 2019

REPORT #E19-307

Extended Motor Products Savings Validation Research on Clean Water Pumps and Circulators

PREPARED FOR:

Warren Fish, XMP Program Manager

Geoff Wickes, XMP Product Manager

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

Executive Summary

Motor-driven systems in the commercial and industrial sectors are an under-tapped area of energy efficiency potential. Recent regulatory and industry advances have begun to take advantage of this potential, with NEEA contributing to this market transformation through the Extended Motor Products (XMP) Initiative. The XMP Initiative is a market intervention initiative aimed at driving awareness, stocking, and sales of efficient motor-driven products through mid-stream incentivization. The first products targeted through the initiative are Clean Water Pumps and Circulators. NEEA worked with the Regional Technical Forum (RTF) to establish "Planning" Unit Energy Savings (UES) Measures for both products. These measures will expire at the end of 2019 if they are not validated through field research. To facilitate this validation, NEEA contracted with Cadeo Group and Energy350 (the research team) to gather and analyze field data on the energy performance of commercial and industrial Clean Water Pumps and commercial and residential Circulators. This project builds on the findings of earlier research[1] from which the Regional Technical Forum (RTF) established the Planning UES Measures[2,3].

The RTF used the best available data to develop the UES Measures, but they had to make certain assumptions and simplifications due to a lack of sufficient information. These assumptions impact variables in the energy savings model developed for the measures, with the largest impacts being the operating hours estimates and the development of an empirical Adjustment Factor, which adjusts the estimated energy savings to account for real-world pump operation and system characteristics.

To validate and improve the RTF Clean Water Pump and Circulator measures, Cadeo conducted a research project, largely based on the RTF's published research plans for each product, with the following goals:

- Characterize the operating hours of pumps installed in various applications in the Northwest
- Characterize the energy consumption of pumps in various applications in the Northwest
- Research and explore the factors that affect the accuracy of the energy savings model developed by the RTF in the development of the UES Measures

Throughout the course of the project, the research team collected and analyzed audit and operational data on 342 Clean Water Pumps and 115 Circulators. The research team leveraged existing data (collected for previous pump incentive projects or monitored through automation systems) as well as primary data to fill the sample strata. In most cases it was not possible to collect a full 12-months of pump data, so the research team developed a rigorous annualization process to convert the submitted raw data to annualized values. This process develops a robust dataset of pump operational data, at 1-hour intervals, which represent a specific pump's operation over the course of one year.

1 Source: SBW Consulting, Inc. "Extended Motor Product Labeling Initiative (EMPLI) Measure Update and Scoping". October 4, 2016. Developed for the Northwest Energy Efficiency Alliance. Available at: https://nwcouncil.app.box.com/s/ilmxuvj0b54617wggpf30rvfw3myo613

2 https://nwcouncil.box.com/v/ComIndAgPumpsv1-1

3 https://nwcouncil.box.com/v/ComResCirculatorPumpsv1-2

Clean Water Pump Results

Overall, for Clean Water Pumps, the collected data validated and confirmed the reasonableness of the original RTF estimates. However, the research did uncover several improvements and updates that will serve to make the updated energy savings from C&I pumps more accurate and precise.

As discussed previously, for Clean Water Pumps, the research addressed two primary variables: operating hours and Adjustment Factor. For operating hours, the operating hours observed in the research agreed closely with the original RTF planning estimates, as shown in Table 1.

Table 1: Pump Operating Hours, Observed and RTF Estimate

RTF Application	Observed Operating Hours	RTF Estimate OpHrs
Commercial HVAC and DHW	3,753	4,000
Industrial and Municipal	5,242	5,000
Agricultural	2,358	2,400

However, there was a fair amount of variability in the observed application-based operating hour estimates, which can be explained by looking at the pump applications on a more granular level. For example, commercial DHW pumps, which are primarily pressure boost pumps in this sample, show significantly more operating hours than standard heating and cooling pumps, as shown in Table 2**.**

Table 2: Commercial Sector Operating Hours

Value	Commercial Sector Average	Research Application Average			
		Cooling Tower	Cooling	Heating	Pressure Boost
Average Operating Hours	3,753	**2,978**	**3,211**	**4,964**	**6,028**

Similarly, when considering industrial and municipal and separate applications, municipal pumps exhibit much lower operating hours than industrial applications, as shown in Table 3. The research team also investigated two separate industrial applications: cooling and boiler feedwater (BFW), which also exhibited significantly different operating hours. Based on these findings, the team recommends a more granular differentiation of operating hours based on, at least, the following applications: Commercial HVAC, Commercial DHW, Agricultural, Industrial, and Municipal.

Table 3: Industrial and Municipal Sector Operating Hours

Value	Combined Average	Industrial Cooling	Industrial BFW	Municipal
Average Operating Hours	5,242	**6,175**	**4,119**	**3,360**

The second primary variable addressed for Clean Water Pumps was Adjustment Factor. The Adjustment Factor included in the Planning Measures accounts for a number of system-level differences between the modeled pump energy use and real-world pump energy use, including motor sizing, load profile, system static head, and the relationship of the pump duty point to the pump's Best Efficiency Point, or BEP (referred to in this research as BEP Offset). The analysis reviewed Adjustment Factor as well as the individual factors that affect Adjustment Factor.

Overall, the **Adjustment Factor** values, which compare the real-world energy consumption to the energy consumption predicted by the RTF simplified energy model for each pump, generally agreed with the approach and magnitude originally estimated by the RTF. Generally, the observed Adjustment Factors were between 0.7 and 1.4 and were higher for both Agricultural pumps and ST pumps than the other sectors and pump classes, respectively. This is consistent with the RTF's assumptions, although the RTF measures separated ST from the other pump classes due to different sizing conventions for submersible pumps. In our research, the motor sizing of ST pumps was found to be similar to other pump classes. However, the Adjustment Factor for ST pumps was still observed to be higher than other pump classes, due to their application in the Agricultural sector (all ST pumps collected are in the Agricultural sector) and the associated load profile and system static head requirements in that application.

Motor Oversizing is the difference between the pump input power at BEP and the Rated Motor Horsepower, which is the key power variable in the RTF simplified energy model. The RTF assumed a constant Motor Oversizing of 120% of Power at BEP, except for ST pumps, which use submersible motors that have a service factor of 1.2 instead of 1.0 (for non-submersible turbine). The pumps collected through this research show an average motor oversizing of 24%, which aligns well with the RTF's original estimate. However, the collected data did not exhibit significantly different motor sizing practices for ST pumps. However, the research team did observe a noticeable dependency between the size of the motor and the motor oversizing, as shown in Figure 1. This may be because the cost of the motor will likely limit the extent of motor oversizing as the size of the motor increases and because differences in nominal HPs represent a larger percentage difference for smaller HP pumps.

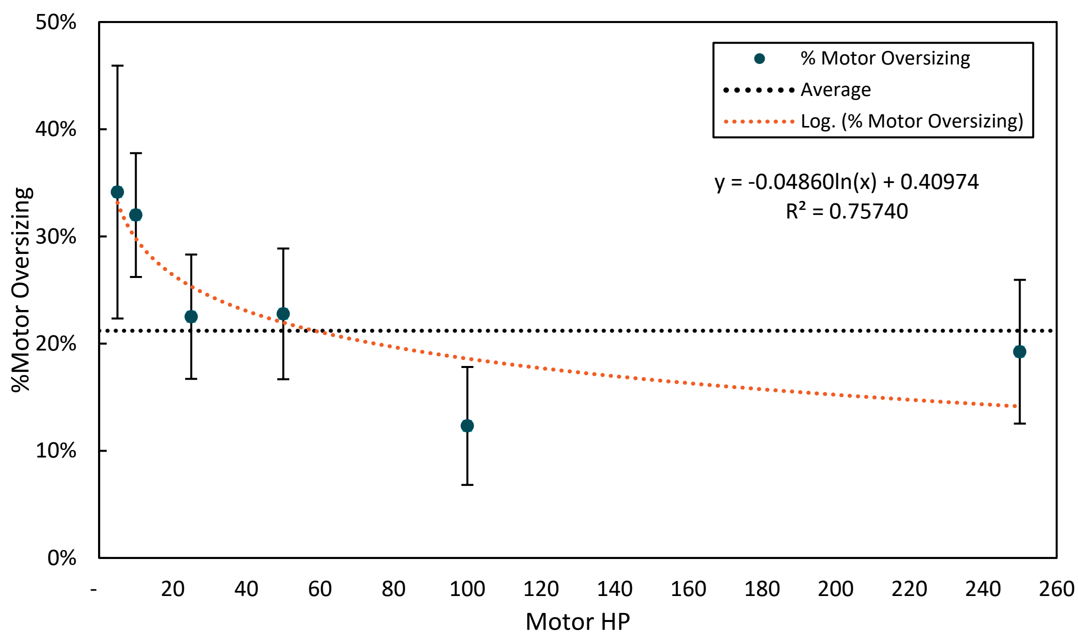

Figure 1: Motor Oversizing vs Motor HP

Static head is the amount of pressure a pump must overcome to start moving water in a system.[4] The RTF assumed static head was dependent on the sector, or application, the pump was installed in; they estimated a static head of 40% of BEP head for Commercial HVAC and DHW Pumps and 20% of BEP head for Industrial and Municipal Pumps. Table 4 shows that the RTF's estimates were very close to the observed values, with Commercial HVAC Pumps having an average static head of 35% and Industrial and Municipal Pump with a static head of 22%. In both cases, the original RTF estimate is within the 90% confidence internal of the observed values.

Table 4: Observed Static Head, by Sector

Static Head	Commercial HVAC and DHW	Industrial and Municipal
RTF Planning Measure Estimate	40%	20%
Average, as Percent of Head at BEP	35%	22%
90% Confidence Interval	29% to 42%	12% to 33%

Load Profile represents where in relation to flow at BEP the pump operates. The RTF used four Load Profiles, with different probabilities of occurrence, to develop load profiles for Constant Speed and Variable Speed Pumps. The data collected through this research indicates that different sectors have different load profiles, likely due to the sizing and operating practices prevalent in each sector.

Figure 2 shows the load profiles, by application, for Constant Speed pumps. The load profiles for commercial and industrial pumps are both very broad spending significant amounts of time across the operating range of the pump, including above 110% of BEP flow. Municipal pumps, however, were much more tightly concentrated around 50 and 75% of BEP flow. Compared to the RTF assumed load profiles, these profiles demonstrate significantly more diversity in pump duty point than assumed by the RTF, which assumed 70% operation at 100% if BEP flow.

[4] While static head is intrinsic to the system and will always be present, the dynamic head is related to the friction within the system and is dependent on flow rate and system design.

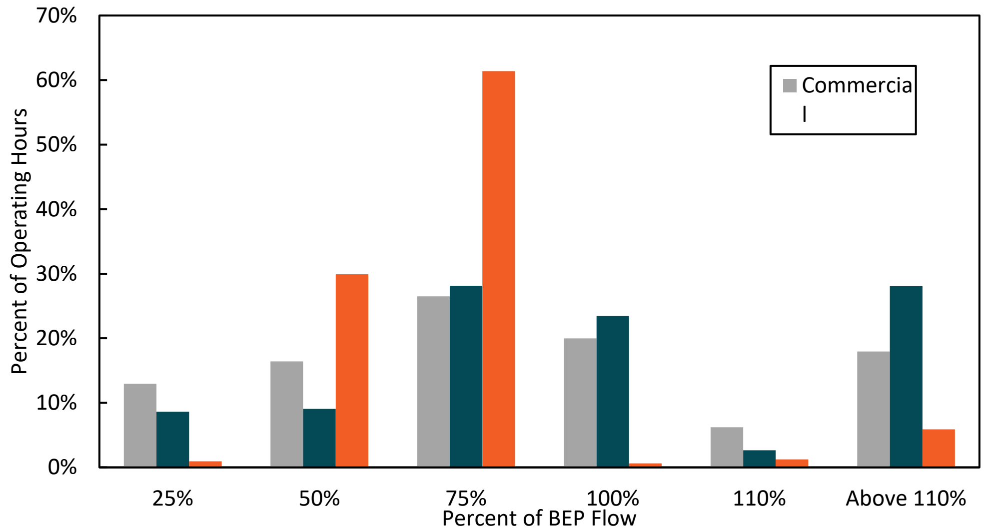

Figure 2: Constant Speed Load Profile, by Sector

Figure 3 show the Variable Speed load profile, which shows significant operation below 50% of BEP flow for commercial and industrial pumps. Pumps in both these sectors spend around 70% of the time below 50% of BEP flow, which is significantly more than the 35% originally assumed by the RTF and represents the potential for significantly more energy savings from variable speed pumps than originally estimated. Municipal pumps, however, exhibited a more constant load profile, centered around 75% of BEP flow, similar to the Constant Speed case.

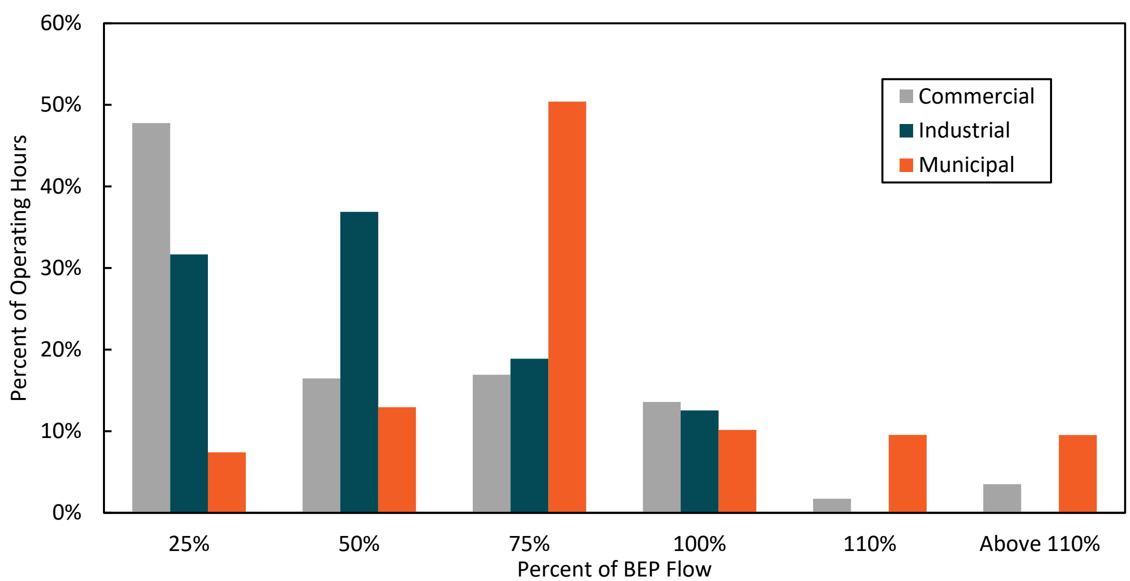

Figure 3: Variable Speed Load Profile, by Sector

BEP Offset is the difference between flow at BEP and flow at the point that the system curve intersects the pump curve. The RTF estimated a range of -25% to +10% flow at BEP. The average BEP Offset for the pumps collected is -17%. However, the range of values observed in the data is quite broad; for the range to cover 90% of the pumps in the sample it would have to be expanded to -76% to +52%.

Based on the dependencies observed in the Adjustment Factor analysis, the research team proposed developing two separate Adjustment Factors, a Motor Oversizing Factor and A Load Profile Factor, that are applied to an updated energy consumption equation,

$$Energy_{pump} = HP * 0.746 * (1 - Factor_{MO,HP}) * OpHrs_A * PEI * Factor_{Adj,A,SC}$$

where

$Energy_{pump}$	=	Annual Pump Energy Consumption, kWh
HP	=	Motor Horsepower (input)
$Factor_{MO,HP}$	=	Motor Oversizing Factor, varies based on Motor HP as shown in Table 62
$OpHrs_A$	=	Operating Hours, varies based on Application (A)
PEI	=	PEI (input)
$Factor_{Adj,A,SC}$	=	Load Profile Adjustment Factor, varies based on Application (A) and Speed Control Case (SC)

A **Motor Oversizing Factor**, which is dependent on the motor HP, and compensates for the difference between the motor's rated HP and the pumps operating HP. The Motor Oversizing Factors are presented in Table 5.

Table 5: Motor Oversizing Factors

Motor HP Range	Representative HP	Number of Pumps	Motor Oversizing Factor
0 - 5 Motor HP	**3**	32	0.3652
5 - 10 Motor HP	**8**	31	0.3118
10 - 25 Motor HP	**20**	48	0.2641
25 - 50 Motor HP	**35**	46	0.2370
50 - 100 Motor HP	**75**	32	0.1999
100 - 250 Motor HP	**150**	21	0.1662

A **Load Profile Factor**, which is dependent on the application and speed control method, and compensates for real world operating characteristics and load profile. The Load Profile Factor accounts for differences in static head, load profile, and BEP offset, all of which are dependent on the application and, in the case of load profile, speed control method. The research team calculated the Load Profile Factors empirically using the annual energy consumption observed through the research, the updated energy consumption equation. Table 6 shows the Load Profile Factors.

Table 6: Load Profile Factor

Application	Constant Speed	Variable speed
Agricultural	1.325	1.845
Commercial	1.250	1.000
Industrial	1.310	1.214
Municipal	0.840	0.990

The Load Profile Factors listed in Table 6 represent the differences between the actual weighted average power consumption and the PEI-estimated weighted average power consumption, accounting for the impact of the actual load profile, static head, and BEP offset on the actual the power consumption.

For constant speed pumps the commercial and industrial load profiles, the load profile factors for agricultural, commercial, and industrial sectors are all higher than 1.000. In these sectors, pumps have more than 25% of their operating hours above 100% flow at BEP, which was not captured in the load profiles used by the RTF, leading to the higher-than-estimated actual energy consumption. Municipal pumps, however, spend the majority of their time at 75% flow at BEP, which is slightly lower than the RTF's assumed load profile. This causes the municipal energy consumption to be lower than that assumed by the RTF (which assumed more operation at 100% of BEP flow) and the Load Profile Factor to be lower than 1.000.

A similar trend is seen with variable speed municipal pumps, where the low Load Profile Factor is adjusting for the time the pump spends at 75% flow at BEP, resulting in an adjustment factor that is lower than 1.000. The commercial and industrial Load Profile Factors are less intuitive. The load profiles for these pumps are weighted around 25% and 50% flow at BEP but the Factors are equal to or larger than 1.000. The static head and BEP offset may be contributing to these factors being higher than 1.000, with either higher static head increasing the energy used at lower flow rates and/or a more negative BEP Offset value driving the system curve and energy consumption up at lower flow rates (i.e., if the BEP offset is below 100% BEP flow, 100% speed will occur at a "reduced" flow rate with respect to BEP, which will result in higher speeds at lower flow rates across the operating range of the pump).

Circulator Pump Results

The Circulator Research focused on investigating the operating hours, average operating power, and water heater energy savings in domestic hot water (DHW) recirculation systems and hydronic heating systems. A particular focus in the circulator analysis was the performance of different control methods, both run-hours controls that impact operating hours and speed controls that affect the speed and input power of the pump when it is on. The research observed a wide variety of control strategies, some of which were not captured or anticipated by the RTF measures, including many different types and combinations of run-hours and speed controls in DHW applications. The research also found that these control strategies also vary by manufacturer in terms of how the control logic is employed, making it difficult to effectively and comprehensively generalize and categorize the results.

Operating Hours. For DHW systems, the research team investigated the operating hours associated with several different run-hour control methods, as shown in Table 7.

Table 7: Operating Hours, DHW Circulators

Sector	Control Variety	Number of Pumps (n)	Average Operating Hours	RTF Estimate
Residential	No Control	5	8,760	8,760
	Timer-Controlled	2	3,469	7,300
	Aquastat	5	3,913	1,095
	On-Demand	1	60	61
	Learning	0	-	1,095
Commercial	No Control	51	8,218	8,760
	Timer-Controlled	13	3,681	6,570
	Aquastat	1	1,527	1,095
	On-Demand	11	1,704	122
	Timer Control with On-Demand Capabilities	4	274	NA
	Learning	0	-	1,095

For timer-controlled pumps in both the residential and commercial sectors, the observed operating hours for DHW systems were lower than the RTF estimate, indicating that timers may be being set more judiciously than the RTF projected. The converse was seen for Aquastat controls, where the data collected showed higher operating hours than the RTF estimate. Residential on-demand had an observed operating hours almost exactly the same as the RTF, although the sample size was small. The research team did not observe or implement any control strategies that met the RTF definition of on-demand[5] in multi-family or commercial settings that would allow the loop to cool down below usable temperatures due to concerns with utility and user satisfaction. Instead. Instead, commercial buildings were often equipped with Aquastat-style controls, Timer controls (some with on-demand functionality), or temperature-based speed control in an effort to reduce pump power and recirculation loop losses. The team was not able to effectively evaluate Learning-based controls due to equipment malfunction and limited sample size based on the nascent nature of this control strategy.

For hydronic heating pumps, the observed operating hours for residential pumps was 3,291 hours, which equates to 4.5 months of operation per year. Commercial Hydronic heating circulators are very uncommon in the field; most often the systems are served by nominal HP Clean Water Pumps so the research team removed them from the sample frame.

Average Input Power. The research team also investigated the average power draw, in Watts, for circulators with different efficiencies and speed controls. As shown in Table 8, the observed average power draw is significantly lower than the RTF Estimate, however, the percent difference between the control strategies is similar. Significant energy savings are seen moving from an induction circulator to an ECM

5

circulator, and then again from adding more advanced variable speed control to the ECM circulator. The reason for the reduced values is that the circulators included in the study spent significantly more time a lower operating points (25 and 50% of BEP flow) than the RTF estimates assumed. In particular, variable speed pumps were observed to spend more than 50% of the time below 25% flow at BEP. The research team believes this is due to a combination of motor and pump oversizing (and the ability of variable speed controls to compensate for this) and the ability of advanced speed control strategies to more closely match the required load in a given application.

Table 8: Average Circulator Power Draw

EL	Description	Weighted Average Power, normalized to 1/25 HP		
		Observed Watts	n	RTF Estimate (Watts)
EL0	**Induction Motor**	62	44	116
EL1	**Efficient Induction Motor**	NA	NA	88
EL2	**ECM**	34	8	51
EL2.5	**ECM with Constant Pressure Controls**	34	8	NA
EL3	**ECM with Proportional Pressure Control**	16	5	41
EL3.5	**ECM with Adaptive Pressure Control**	10	10	38
EL4	**ECM with Differential Temperature Controls**	11	10	30

Water Heater Energy Savings. The water heater energy savings are an important component of savings for DHW circulator pumps. The water heater energy savings were estimated based on changes in average recirculation loop temperatures[6] resulting for the different control strategies on the same system. The percent difference, which is representative of the relative reduction in energy losses in the piping for that system and control strategy, is the percent energy savings, which are presented in Table 9. As shown in the table, the greatest energy savings were, in general, associated with run-hours controls, which are highlighted in grey. The largest energy savings were seen by the site that employed learning controls, however the research was only able to collect information on one site using these controls and the state logger failed on this site so we are unable to determine how often the pump ran to corroborate these water heater energy savings. The relative efficacy of each control type varied by sector, but due to small sample sizes and variability between the sites it is difficult to reach conclusive findings related to the absolute impact of different control strategies on water heater energy consumption.

[6] The average supply temperature and average return temperature were calculated for each pump, and then the average of those two values was calculated.

Table 9: Water Heater Energy Savings

Sector	Speed Control	Timer Control	% Energy Savings[7]	n
Single Family Residential	No Control	No Control	-	3
	No Control	Learning	37.08%	1
	No Control	Temperature	6.49%	5
	Adaptive Pressure	No Control	7.91%	1
	Differential Temperature	No Control	0.29%	1
Multi-Family Residential	No Control	No Control	-	8
	No Control	On-Demand*	15.52%	4
	No Control	Temperature	14.54%	1
	Constant Pressure	No Control	4.98%	1
	Proportional Pressure	No Control	6.29%	2
	Adaptive Pressure	No Control	1.05%	3
	Differential Temperature	No Control	0.16%	1
Commercial	No Control	No Control		6
	No Control	On-Demand	1.35%	1
	No Control	Timer	14.57%	3
	Constant Pressure	No Control	2.62%	2
	Proportional Pressure	No Control	2.45%	1
	Differential Temperature	No Control	3.72%	3
	Constant Pressure	Timer	4.25%	2
	Adaptive Pressure	Timer	4.38%	2
	Differential Temperature	Timer	0.90%	4

Additional Insights. The research team also identified some additional insights gleaned through the data collection and pump replacement process.

- There is a lack of continuity in the nomenclature used to label controls. Often times the same term is used to indicate both run-hours- and speed- control mechanisms or different terms are used to identify the same style of control, which leads to confusion within the market.
- The advanced control strategies did not create a disruption in service (either delays in hot water time-to-tap or space heating efficacy), and were not mentioned by any sites as a source of issue.
- Due to the general acceptance of the advanced control strategies tested, none of the controls were reverted back to no control.

[7] The number of places after the decimal point in this column was increased to allow for comparison of the pumps that had less than 1% Energy Savings

- Almost all previously installed circulators were operated without controls. This is indicative of a low penetration of controls within the market, despite the recent code requirements related to on-demand controls in commercial and multi-family buildings.

This research represents an important contribution towards better understanding and characterizing pump operation and energy consumption in the Pacific Northwest. Based on these findings, the research team recommends revisiting the Clean Water Pumps and Circulator Pumps measures to incorporate the updated findings and dependencies to improve the energy savings estimates, especially for Clean Water Pumps. For Circulator Pumps, given the variety of applications and diversity of control strategies, it was more difficult to accurately characterize the improvements from different control strategies and additional research may be needed in some areas, especially multi-family hydronic heating, in order to further inform the potential energy savings from the variety of control strategies offered by manufacturers. This report also only represents the first step in analyzing the wealth of pump data collected as part of this research and the research team looks forward to additional findings from future researchers who may leverage the database to answer additional questions.

Table of Contents

Executive Summary ... 3
Table of Contents ... 14
List of Tables ... 16
List of Figures ... 19
1 Introduction ... 20
2 Background ... 21
2.1 Federal Standards for Motor-Driven Products ... 22
2.2 Extended Motor Products Labeling Initiative ... 23
2.3 Hydraulic Institute's Energy Rating Label ... 24
2.4 NEEA's Extended Motor Products Initiative ... 25
3 Research Overview ... 26
3.1 General Research Design ... 26
3.2 Research Oversight ... 27
4 Clean Water Pumps Research ... 29
4.1 RTF Unit Energy Savings Measures ... 29
4.1.1 Energy Savings Model ... 31
4.1.2 Assumptions and Research Questions ... 32
4.2 Data Collection Methodology ... 34
4.2.1 Data Sources ... 35
4.2.2 Sample Strata ... 35
4.2.3 Data Collection Outcomes ... 37
4.2.4 Data Standardization and Annualization ... 42
4.3 Results and Discussion ... 53
4.3.1 Operating Hours ... 53
4.3.2 Adjustment Factor ... 66
5 Circulator Research ... 91
5.1 RTF Unit Energy Savings Measures ... 91
5.1.1 Energy Savings Model ... 95
5.1.2 Assumptions and Research Questions ... 97
5.2 Data Collection Methodology ... 100

5.2.1 Data Sources 100
5.2.2 Sample Strata 101
5.2.3 Data Collection Outcomes 102
5.2.4 Data Standardization and Annualization 104
5.3 Review of Existing Literature 106
5.3.1 Domestic Hot Water Recirculation 106
5.3.2 Hydronic Heating 110
5.4 Results and Discussions 111
5.4.1 Classification of Control strategies 111
5.4.2 Operating Hours 114
5.4.3 Average Operating Power 118
5.4.4 Water Heater Energy Savings 123
5.4.5 Additional Insights 125
6 Conclusions 126
7 Acknowledgements 130
8 References 131
9 Appendices 133
9.1 Data Submission Form 133
9.2 Data Management Plan 133
1. Existing Data Collection Steps: 134
1.1 Before Data is Submitted 134
1.2 After Data is Submitted 135
2. Audit Data QA/QC Steps 136
2.1 For Efficient C&I Pumps 137
2.2 For Circulators 138
2.3 For Optional Efficient C&I Data 138
2.4 For Operational Circulator 138
2.5 Literature Values 138
3. Operational Data QA/QC 139
3.1 Raw Operational Data Standard Formatting 139
9.3 Database User Guide 145

List of Tables

Table 1: Pump Operating Hours, Observed and RTF Estimate 4
Table 2: Commercial Sector Operating Hours 4
Table 3: Industrial and Municipal Sector Operating Hours........ 4
Table 4: Observed Static Head, by Sector 6
Table 5: Motor Oversizing Factors 8
Table 6: Load Profile Factor 9
Table 7: Operating Hours, DHW Circulators 10
Table 8: Average Circulator Power Draw 11
Table 9: Water Heater Energy Savings........ 12
Table 10: Technical Work Group Membership 27
Table 11: RTF Assumed Operating Hours 32
Table 12: Static Head by Pumping Application 34
Table 13: RTF Proposed Sample Sizes for Data Collection........ 36
Table 14: Data Collection Targets, Newly Metered Samples and Existing Data Samples 37
Table 15: Pumps identified in Commercial Cooling Tower Application........ 38
Table 16: Pumps identified in Commercial Cooling Application........ 39
Table 17: Pumps identified in the Commercial Heating Application 39
Table 18: Pumps identified in the Commercial Pressure Boost Application 39
Table 19: Pumps identified in the Commercial Domestic Hot Water Circulation Application 40
Table 20: Pumps identified in the Agricultural Irrigation Application 40
Table 21: Pumps identified in the Municipal Water Treatment/Conveyance Application........ 41
Table 22: Pumps identified in the Industrial General Application........ 41
Table 23: Pumps identified in the Industrial BFW Application 41
Table 24: Pumps identified in the Industrial Cooling Application 41
Table 25: Final Sample Strata with Adjusted Targets 42
Table 26: Audit Information and purpose for collection, Clean Water Pumps 43
Table 27: Minimum collection timeframes established by Research Plan........ 47
Table 28: Crosswalk between RTF Measure Applications and Research Applications........ 53
Table 29: Average Agricultural Pump Operating Hours and Statistical Analysis, observed and RTF Estimate 56
Table 30: Average Observed Agricultural Pump Operating Hours and Statistical Analysis, without BPA Data........ 56
Table 31: Agricultural Pumps, Average Operating Hours by Motor HP Range, Statistical Analysis 58
Table 32: Average Operating Hours and Statistical Analysis, Commercial HVAC and DHW........ 59
Table 33: Average Commercial HVAC and DHW Operating Hours, Statistical Analysis by motor HP 60
Table 34: Average Commercial HVAC and DHW Operating Hours, Statistical Analysis by motor HP Bin .. 61
Table 35: Average Commercial HVAC and DHW Operating Hours, Statistical Analysis by Speed Control Method 61
Table 36: Average Commercial Sector Operating Hours, Statistical Analysis by Application........ 62
Table 37: Average Commercial HVAC and DHW Operating Hours, Statistical Analysis by speed Control Method with Pressure Boost removed........ 63

Table 38: Commercial HVAC pumps Operating Hours, Statistical Analysis by Application and Speed Control Method ... 63
Table 39: Industrial and Municipal Operating Hours, Statistical Analysis ... 64
Table 40: Industrial and Municipal Operating Hours, Average by Sector ... 65
Table 41: Industrial Observed Operating Hours, by Application ... 66
Table 42: Observed Adjustment Factor, Statistical Analysis ... 67
Table 43: Adjustment Factor Statistical Analysis, by Speed Control Method ... 70
Table 44: Average Observed Adjustment Factor, by Pump Class and Nominal Speed ... 71
Table 45: RTF Assumed Adjustment Factors ... 72
Table 46: Observed Adjustment Factor, Disaggregated ... 74
Table 47: Percent Motor Oversizing Statistical Analysis ... 75
Table 48: Motor Oversizing Statistical Analysis, grouped by Motor HP ... 76
Table 49: Average Motor Oversizing, by Pump Class ... 77
Table 50: Average Static Head, All Pumps ... 78
Table 51: Average Static Head, by RTF Application ... 79
Table 52: Average Static Head, by Research Application ... 79
Table 53: Observed Load Profile Statistical Analysis ... 80
Table 54: Statistical Analysis, Constant Speed Load Profile ... 82
Table 55: Statistical Analysis, Variable Speed Load Profile ... 83
Table 56: Statistical Analysis, Commercial Load Profile ... 84
Table 57: Statistical Analysis, Industrial Load Profile ... 84
Table 58: Statistical Analysis, Municipal Load Profile ... 85
Table 59: Average BEP Offset and Statistical Analysis, All Pumps ... 86
Table 60: Average BEP Offset and Statistical Analysis, by Speed Control Method ... 87
Table 61: Summary of Adjustment Factor Sub-Factors and Dependencies ... 87
Table 62: Motor Oversizing Factor, by Motor HP Bins ... 88
Table 63: Final Load Profile Adjustment Factors, by Application and Speed Control Case ... 89
Table 64: Summary of Circulator Measure Identifiers ... 91
Table 65: Nominal HP Sizes with corresponding HP Range and Max Watt Rating ... 93
Table 66: Speed Control Methods for Circulators ... 93
Table 67: Baseline Operating Hours, Hydronic Heating ... 96
Table 68: Baseline Operating Hours, Domestic Hot Water recirculation ... 96
Table 69: RTF UES Measure Hydronic Heating Operating Hours ... 99
Table 70: RTF UES Measure DHW Operating Hours ... 99
Table 71: RTF Circulator Sample Targets ... 101
Table 72: Final Sample Frame Sample Disposition ... 102
Table 73: Audit Information and purpose for collection, Circulators ... 104
Table 74: Single Family Domestic Hot Water Literature Summary ... 107
Table 75: Multifamily Domestic Hot Water Literature Summary ... 109
Table 76: Commercial Domestic Hot Water Literature Summary ... 110
Table 77: Speed Control Strategies and Definitions ... 111
Table 78: Run-Hour Control Strategies and Definitions ... 112
Table 79: DHW Circulator Operating Hours, Observed vs RTF Estimate ... 115
Table 80: Observed Operating Hours, Hydronic Heating ... 117

Table 81: Observed Operating Hours, Hydronic Heating by Speed Control Method 117
Table 82: Operating Hours - Hydronic Heating Circulator replacement 118
Table 83: Average Operating Power (Watts), by Nominal HP and Efficiency Level................................. 118
Table 84: Weighted Average Operating Power, (Watts for a 1/25 HP circulator).................................. 119
Table 85: Circulator Load Profile by Efficiency Level, all Circulators 120
Table 86: Circulator Load Profile by Efficiency Level, Hydronic Heating 121
Table 87: Circulator Load Profile by Efficiency Level, Domestic Hot Water Recirculation 121
Table 88: Average Percent Decrease in Power for Pump Swaps... 123
Table 89: Percent Hot Water Energy Savings, by Sector and Control Strategy 124
Table 90: Data Management Roles and Role Responsabilities 133
Table 91: Pump Nominal Speeds 138

List of Figures

Figure 1: Motor Oversizing vs Motor HP 5
Figure 2: Constant Speed Load Profile, by Sector 7
Figure 3: Variable Speed Load Profile, by Sector 7
Figure 4: Hourly Flow Rates over the course of one day, for all pumps 50
Figure 5: Agricultural Operating Hours, by Motor HP 57
Figure 6: Average Commercial HVAC and DHW Operating Hours, by Motor HP 59
Figure 7: ‘Commercial HVAC and DHW’ Operating Hours, by motor HP 62
Figure 8: Industrial and Municipal Operating Hours, Average by Sector 65
Figure 9: Histogram of Adjustment Factor, All Pumps 68
Figure 10: Observed Adjustment Factor vs Operating Hours 68
Figure 11: Observed Adjustment Factor vs Motor HP 69
Figure 12: Observed Adjustment Factor vs PEI 69
Figure 13: Histogram of Adjustment Factor, Constant Speed Pumps 70
Figure 14: Histogram of Adjustment Factor, Variable Speed Pumps 71
Figure 15: Adjustment Factor by Pump Class and Nominal Speed 72
Figure 16: Adjustment Factor by Pump Class 73
Figure 17: Adjustment Factor by Sector 73
Figure 18: Percent Motor Oversizing vs Motor HP 75
Figure 19: Percent Motor Oversizing vs Motor HP, by Motor HP Bin 76
Figure 20: Observed Load Profile, All Pumps 80
Figure 21: Constant Speed Load Profile, Observed and RTF Estimated 81
Figure 22: Variable Speed Load Profile, Observed and RTF Estimated 82
Figure 23: Constant Speed Load Profile, by Sector 83
Figure 24: Variable Speed Load Profile, by Sector 84
Figure 25: Histogram of BEP Offset, as a Percent of BEP 86
Figure 26: BEP Offset, Graphical Representation 90

1 Introduction

Motor-driven systems in the commercial and industrial sectors consume a substantial amount of energy. Industrial motor-driven systems use approximately 23% of all electricity sold in the United States (DOE 2002), and commercial systems also have significant energy consumption. Optimizing the energy efficiency of motor-driven products not only saves end users money by decreasing the energy needed to run the equipment, but also decreases unnecessary wear on the equipment. With motors constituting a major energy end-use at many commercial and industrial sites (DOE 2001) a more efficient motor-driven product can have a significant impact on total cost of operation for a facility.

The energy consumption of a motor-driven product depends on system characteristics, installation configuration, and operational methods. This has created a belief within the energy efficiency community that motor-driven products and systems are too variable for prescriptive energy savings measures. Currently, custom energy efficiency programs for motor-driven products focus on large horsepower systems because their potential for large energy savings can offset the Measurement and Validation (M&V) costs associated with custom energy efficiency programs. However, dedicating custom program resources to systems with smaller motors is often not cost effective. This has created a gap in utility energy efficiency program portfolios—a category of equipment (small- to mid-range motor-driven products) that are, historically, considered too complex to address with deemed energy savings programs and too small to merit custom program attention.

The Northwest Energy Efficiency Alliance's (NEEA's) Extended Motor Products (XMP) Initiative seeks to fill this gap. NEEA took advantage of the opportunity to leverage current market movement due to federal standards and rating/labeling efforts from industry, and targeted the XMP Initiative at developing deemed, mid-stream incentives for small- to mid-range motor-driven products (NEEA 2018). XMP's initial focus is Clean Water Pumps and Circulators, which NEEA estimates could save between 50 and 100 aMW in the Northwest over 20 years. [8]

With the goal of supporting programs focused on Clean Water Pumps and Circulators the Regional Technical Forum (RTF)[9] recently approved planning measures for commercial and industrial pumps (Clean Water Pumps)[10] and Circulator pumps (Circulators). These planning measures serve as the basis for incentive programs and support NEEA's XMP Initiative. However, they are provisional and will expire in December 2019 and March 2020 unless all, or a subset of them, are turned into Proven UES Measures. To "Prove" these measures the RTF needs better data about pump energy use and operation to confirm or update the current planning UES estimates. Section 2 includes more information on the RTF measures, as well as federal standards for motor-driven products and NEEA's XMP Initiative.

---

[8] Based on analysis performed by Cadeo, which estimates the potential for pumps including more efficient motors and drives based on the latest RTF Measure analysis (ComIndAgPumps_1_1.xlsx and ComResCirculatorPumps_1_2.xlsx, both available on the RTF website).

[9] The Regional Technical Forum (RTF) is a coordinating body operated by the Northwest Power Planning Council for the benefit of all regional utilities with the goals of standardizing protocols for verifying and evaluating conservation savings and ensuring that the region continues to meet the Council's targets for securing cost-effective conservation. For more information, see https://rtf.nwcouncil.org/.

[10] The scope of commercial and industrial pumps is the same as the scope of DOE's recently adopted test procedure and standards for commercial and industrial pumps. 81 FR 4086 (Jan. 25, 2016) and 81 FR 4368 (Jan. 26, 2016).

To collect the data needed to validate these measures, NEEA partnered with Cadeo Group and Energy350 (the research team) to conduct primary research on pump performance in the Northwest. The primary goal of this research is to gather the necessary data to validate and improve the savings estimates for the Clean Water Pump and Circulator planning measures in support of advancing the suite of measures to the Proven category. To validate the energy savings estimates, the team investigated the individual variables that impact the RTF's energy savings model, as described in more detail in Sections 4.1 and 0 for Clean Water Pumps and Circulators, respectively.

In addition, the data and analysis performed in this study presents new, robust information about pump energy use and energy savings opportunities in the region. Specifically, the research team has developed a database of characteristic information for all pumps included in the research. Many different organizations and industries are collecting and analyzing pump audit and operational data, but their data collection serves diverse purposes: some are collecting the data for energy savings estimates, others are collecting the data to understand system operation. That diversity has prevented the data from being standardized and stored in one location. This research produced a standardized database of operational information from Clean Water Pumps and Circulators which NEEA will make accessible to other parties.

This report presents the results and analysis from field studies with the goal of characterizing two different types of equipment: Clean Water Pumps and Circulators. This report separates them into two different equipment classes based on recommendations made during the Department of Energy's (DOE) Rulemaking Process because of the unique application and equipment configuration of Circulators. DOE felt the differences between Clean Water Pumps and Circulators were large enough to merit separate rulemakings. The RTF also took those differences into consideration in the development of the UES measures.

While this report addresses Clean Water Pumps and Circulators separately, high-level conclusions are combined and presented in Section 6 because they are not equipment specific.

The remainder of this report presents the methodology and results of the research in five main sections:

2. Background
3. Research Overview
4. Clean Water Pumps Research
5. Circulator Research
6. Conclusions

The Data Management Plan, Data Collection Template, and Database User Guide are included as Appendices to this report. The raw and annualized data are also available in a public database for further review and analysis by other researchers.

2 Background

The XMP Initiative takes advantage of recent work done by DOE, industry associations, energy efficiency organizations, and pump manufacturers to advance different aspects of pump efficiency. Section 2 reviews three key advancements that predicated the XMP Initiative: federal standards, the Extended Motor

Products Labeling Initiative, and the Hydraulic Institute's Energy Rating label. Finally, this section includes a discussion of how these advancements have informed the XMP Initiative's development.

2.1 Federal Standards for Motor-Driven Products

In 2016 the Department of Energy (DOE) published a final rule establishing energy conservation standards for certain commercial and industrial pumps (81 FR 4368). This standard is set to take effect on January 27th, 2020. In this rulemaking, DOE established a framework for driving efficiency within the pump market by establishing a new test method and metric, Pump Energy Index (PEI), that allows a purchaser to directly compare the efficiency of different pumps, inclusive of motors and drives that may be sold or packaged with the pump.

PEI is a unitless metric that rates the efficiency of pumps and pumping systems. PEI is the ratio of the weighted average input power of the rated pump to the weighted average input power of a minimally compliant pump. A minimally compliant pump has a PEI of 1.0 and a more efficient pump has a PEI less than 1.0.

The calculation of PEI depends on the controls with which the pump is sold. If the pump is sold as a bare pump or with a motor but without continuous controls,[11] the applicable metric is constant load PEI (PEI_{CL}), calculated as

$$PEI_{CL} = \frac{PER_{CL}}{PER_{STD}} = \frac{(0.3333 \times P_{in,75\%}) + (0.3333 \times P_{in,100\%}) + (0.3333 \times P_{in,110\%})}{PER_{STD}} \quad (1)$$

where

PEI_{CL}	=	Constant Load PEI
PER_{CL}	=	Weighted average driver power input to the motor at 3 separate load points, 75% of flow at Best Efficiency Point (BEP flow), 100% BEP flow, and 110% BEP flow
$P_{in,x\%}$	=	Driver power input to the motor at x% of BEP flow
PER_{STD}	=	The PER_{CL} for a pump of the same equipment class that is minimally compliant with energy conservation standards serving the same hydraulic load (hp)

If a pump is sold with a motor and continuous controls then the applicable metric is variable load PEI (PEI_{VL}), which accounts for the presence of a drive by allowing for reduced speeds along an increased number of load points, as follows

$$PEI_{VL} = \frac{PER_{VL}}{PER_{STD}} = \frac{(0.25 \times P_{in,25\%}) + (0.25 \times P_{in,50\%}) + (0.25 \times P_{in,75\%}) + (0.25 \times P_{in,100\%})}{PER_{STD}} \quad (2)$$

where

PEI_{VL}	=	Variable Load PEI
PER_{VL}	=	Weighted average driver power input to the motor at 4 separate load points, 25% BEP flow, 50% BEP flow, 75% BEP flow, and 100% BEP flow

[11] DOE defines continuous controls as "a control that adjusts the speed of the pump driver continuously over the driver operating speed range in response to incremental changes in the required pump flow, head, or power output." 10 CFR 431.462. This includes variable speed and variable frequency drives.

$P_{in,x\%}$	=	Driver power input to the motor at x % of BEP flow
PER_{STD}	=	The PER_{CL} for a pump of the same equipment class that is minimally compliant with energy conservation standards serving the same hydraulic load (hp)

Regardless of the speed control[12] of the rated pump, PER_{STD} is always calculated as the PER_{CL}. This allows for PEI to account for the presence of a variable frequency drive, or continuous control, in the pump rating. Pumps with continuous controls typically have a PER_{VL} between 0.4 and 0.6, whereas pumps without continuous controls typically have a PER_{CL} between 1.0 and 0.8.

The rulemaking for commercial and industrial pumps also included the recommendation that DOE consider a separate standard for Circulators because of their unique application (US DOE 2015). This recommendation led to the establishment of a Working Group for circulator pumps in 2016 (81 FR 5658 (Feb. 3, 2016)). The work of DOE's Circulator Working Group led to consensus recommendations on a number of items, including a test procedure and standard, as well as establishing a version of PEI specific to Circulator Pumps (ASRAC 2016). The calculation used for the version of PEI developed for Circulators is very similarly to PEI for Commercial and Industrial Pumps,

$$PER_{Circ} = \sum_i w_i (P_{in,i}) \quad (3)$$

$$PEI_{Cir} = \frac{PER_{Circ}}{PER_{STD,Circ}} = \frac{\sum_i \omega_i (P_{in,i})}{PER_{STD,Circ}} \quad (4)$$

where

PEI_{Circ}	=	Circulator PEI
PER_{Circ}	=	PER of the rated pump
$PER_{STD,Circ}$	=	PER of a minimally compliant pump
ω	=	Weighting at each test point
P	=	Power input to the driver at each test point
i	=	Test points, 25%, 50%, 75%, 100%, of BEP

DOE has since slowed down their standards development process and has taken no action on the Working Group's recommendations.

2.2 Extended Motor Products Labeling Initiative

During DOE's rulemaking proceedings for Commercial and Industrial Pumps, industry actors[13] saw the opportunity to leverage DOE's work to advance labeling of motor-driven products (Rogers 2014). This

[12] DOE uses the terminology "Load Control" to distinguish between the presence or absence of continuous controls, however, the RTF Measures, and subsequently this research, use the term "speed control" to avoid confusion with other aspects of load management (e.g., the absence of continuous controls does not mean the pump cannot operate at various load points, it simply means it is less efficient at other load points).

[13] Industry actors includes manufacturers of motor-driven products, industry associations, and members of the energy efficiency industry.

resulted in the American Council for an Energy-Efficient Economy (ACEEE) convening the Extended Motor Products Labeling Initiative.

The motor-driven products industries established the Extended Motor Products Labeling Initiative, or EMPLI, as a collective of over 24 representatives from different organizations and industries that can support the advancement of motor-driven systems, including trade organizations, equipment manufacturers, energy efficiency organizations, and utilities. The goal of EMPLI was to develop labels for three different motor-driven products (pumps, fans, and compressors) that enable prescriptive incentive programs for these products[14]. EMPLI established three working groups to address the three different motor-driven products and determine what a label for each product should include.

2.3 Hydraulic Institute's Energy Rating Label

The Hydraulic Institute (HI), which is the industry association for pump manufacturers, was involved in DOE's development of the new PEI metric and test procedure. Based on the framework DOE established, HI has created an industry-driven voluntary rating and labeling system that builds on the foundation DOE established. HI's rating is based on a new metric, called the Energy Rating (ER),[15] calculated directly based on PEI, as shown in Equation 5. HI designed the Energy Rating to be more customer facing by ranking pump efficiency more intuitively (with higher ER values representing higher efficiency ratings).

$$ER = \left(1.00 - PEI_{\frac{CL}{VL}}\right) * 100 \qquad (5)$$

Pumps compliant with DOE's standard have ER values greater than zero, which describe the percentage difference in PEI between the rated pump and the minimally compliant pump. Under this system, higher ERs are associated with more efficient pumps.

Along with a label that explicitly presents the relative power consumption of the pump, HI also developed an online database where pump manufactures can list the ER and PEI of certified pumps, creating an industry-wide catalog of pump efficiency information.[16]

The HI ER Program also builds on DOE's requirements by:

- requiring participating manufacturers to label pumps with a specifically designed label that describes how that product compares to other similar pumps (similar to the Energy Guide label for consumer appliances)
- requiring all product testing in third party certified laboratories[17]
- allows for rating, labeling, and listing of pumps in HI's certified product database prior to 2020 (when DOE's certification will be required)

[14] A "prescriptive program" refers to an incentive that is valued, in terms of both the energy saved and the cost incurred, on a standardized scale. The savings are established on an energy/unit basis. The standardization of the energy savings allows for these programs to be economically applied on a large scale.
[15] See http://pumps.org/EnergyEfficiency/Energy_Rating.aspx
[16] HI's Energy Rating Database can be found at http://er.pumps.org/ratings/search
[17] HI's Pump Test Lab Approval Program (HI 40.7) is described in more detail here: http://pumps.org/Source/Wireframes/EnergyOneColumn.aspx?pageid=2811

- allowing pumps not considered by DOE's current pump test procedures and regulations to berated, labeled, and listed. This, including Circulators[18] and pump with motors and drives that are added after the point of manufacturer[19]

2.4 NEEA's Extended Motor Products Initiative

With the motor-driven products community aligned on standardizing the energy metrics and developing labels for motor-driven products through EMPLI, NEEA took the next step towards accelerating the adoption of efficient motor-driven products by starting the XMP Initiative. The goal of the initiative is to drive awareness, stocking, and sales of efficient motor-driven products through mid-stream incentivization and to influence federal standards over time. NEEA envisioned the initiative as a cost-effective way for the region to capture energy savings from the market adoption of energy efficient motor-driven products. XMP focuses on smaller motor-driven products because custom utility programs typically do not incent them due to the lower incremental savings associated with smaller equipment. This lower incremental savings cannot justify the M&V resources needed for a custom project. NEEA's initiative targets the mid-stream portion of the market, specifically intervening at the distributor level. There are certain market characteristics that make mid-stream intervention a more practical and effective strategy. These include:

- First Cost – End users typically focus on the initial cost of the piece of equipment. They do not usually consider the lifetime cost of ownership, including maintenance and energy costs. Often a purchaser would request input from the distributor or manufacturer's representative as to what equipment would fit their specific need and then choose from that list based on first cost.
- Split Incentive – Often the equipment buyer or specifier does not pay the ongoing costs of the pump. For example, a design and construction firm may win a contract to construct a building; this ties them to a specific cost for the project, incentivizing them to buy inexpensive motor-driven products, without considering the lifetime costs associated with them.
- Complexity – Motor-driven products are complex products and customers often do not have enough information to select the best products for their specific application. They often defer to the distributor, who may not have a complete understanding of the mechanical and operational components of the system.
- Awareness – Often buyers are not aware of the efficiency of the products they are purchasing relative to other options and do not use this as a factor in their selection process.
- Velocity of Sales – The purchase of these products is often on an urgent basis; the product is either needed to replace a failed piece of equipment or it is part of a larger project that is focused on other facets of the job and doesn't allow for a thorough review of each product's efficiency.

The standard that DOE established for Commercial and Industrial Pumps, as well as the progress that was made on establishing an energy conservation standard for Circulators, led NEEA to initially focus on small pumps and pump systems (below 50 HP), with plans to start work on other motor-driven products, such as fans and compressors, in the future.

[18] as described earlier, DOE has not yet taken action on circulators and, therefore, no federal standard or test procedure exist

[19] DOE's test procedure and metric only apply to equipment at the point of manufacturer. However, sometimes, motors or continuous controls are added to a bare pump at the distributor, which is not accounted for in DOE's rating system.

NEEA worked with the RTF to establish the UES Measures for Clean Water Pumps and Circulators. An RTF UES Measure includes measure identifiers, used to specify the equipment's configuration, as well as an energy savings estimate and incremental cost of the measure for each combination of measure identifiers. The XMP Initiative's mid-stream target necessitated measure identifiers that could be determined at the distributor level, and the distributor typically does not know who will purchase a product at the time the distributor decides to stock the product. This means the energy savings and incremental cost must be able to be determined before the end-user is known.

Both the Clean Water Pump measures and Circulator measures have been categorized as "Planning Measures", which indicates the methodology and information used to develop them is sound, but field research is needed to prove the validity of the energy savings estimates for them to be considered "Proven". The RTF published research strategies for both measure sets which outline the assumptions and engineering judgment which need validation, as well as a possible research method.[20]

For NEEA to proceed with the XMP Initiative for pumps they need Proven RTF UES Measures for Clean Water Pumps and Circulators. This led NEEA to complete the research outlined in Section 3 of this report.

3 Research Overview

To validate the energy savings estimates associated with the RTF's Clean Water Pump Measures and Circulator Measures NEEA partnered with Cadeo and Energy350 to research pump operation in the Northwest. The research focused on validating the assumptions the RTF highlighted as requiring field research to verify. The research team used the Research Strategies published by the RTF to inform the development of the methodology for this research.

3.1 General Research Design

The RTF designed the research plans for Clean Water Pumps and Circulators (Included in Appendix A) to assess the validity of assumptions impacting the energy savings estimates associated with the UES Measures. The research also aimed to explore how the different aspects of the energy savings model varied based on installation characteristics of the pump (e.g., application, motor size, variable speed drive configuration). Both the Clean Water Pump research and the Circulator research intended to rely heavily on the collection of existing data, with newly metered pumps serving as a method of completing the sample strata.

The research plan proposed to gather data on pumps to create representations of pump energy consumption based on their rated average power consumption and the other characteristics of the application. As described in more detail in Section 4 and Section 5, for both the Clean Water Pump and Circulator measures, there are several key variables that impact the energy savings estimates. Both measures are fundamentally constructed to estimate savings based on two primary factors: (1) a

---

[20] The research plans for Clean Water Pumps and Circulators can be found at https://rtf.nwcouncil.org/measure/efficient-pumps and https://rtf.nwcouncil.org/measure/circulator-pumps, respectively.

difference between the average power consumption of the baseline and efficient case pump and (2) the operating hours for each application.

The PEI or PER[21] is used to describe the efficiency of a given pump system and the difference in power consumption between the baseline and efficient case. This research investigates how representative the PEI and PER ratings are of real-world power consumption for pumps of various efficiencies and applications. The research also investigated the operating hours for different pump systems, which the research team expects to vary primarily by application.

This research is designed to investigate the power consumption characteristics and operating hours for all pumps, as a function of pump efficiency (PEI or PER) and application, among other things.[22] In this way, the research investigates what drives pump energy use and savings more generally, rather than a specific pre-defined baseline and efficient case. The data collected will be applicable to both baseline and efficient case scenarios.[23] In addition, the results and findings will be more flexible and transparent so that the energy efficiency industry can continue to use them if the baseline and/or efficient case is updated to reflect future market changes.

NEEA is publishing these pump performance data and attributes in a Pump Performance Database accompanying this report.

3.2 Research Oversight

The research team established a Technical Work Group (TWG) in March 2018 to provide input and guidance to the research team and support the implementation of the research plan. The TWG membership consisted of regional stakeholders, Clean Water Pump and Circulator manufacturers, subject matter experts, and representatives from utilities in the Northwest. Table 10 shows the organizations that participated in the TWG along with their representative.

Table 10: Technical Work Group Membership

Organization	Name
Armstrong Fluid Technology	Brent Ross
Armstrong Fluid Technology	Gabor Lechner
Avista Corp	Andy Paul
Bonneville Power Administration	Erin Hope
Bonneville Power Administration	Todd Amundson
Energy Trust of Oregon	Kenji Spielman
Grundfos	Chris Ireland
Hurley Engineering	Devin Carle
Hydraulic Institute	Edgar Suarez
Idaho Power	Randy Thorn

[21] PER is a derivative of PEI, where PEI is calculated as PER of the rated pump divided by the PER of a minimally compliant pump.
[22] The RTF measures define measure identifiers that impact the energy use and energy savings of pump systems. The research will investigate the savings variables based on all these identifiers to confirm the importance of each identifiers and it's impact on estimated savings.
[23] This assumes that the characteristics of the pump application (the sector, type of pump it is, whether it is variable speed, etc.) will describe the load the pump is serving, which will not vary based between the efficient and baseline case, similar to a house heating load which does not vary based on the efficiency of the heating system. The research will verify this is the case in the course of analysis.

Organization (cont.)	Name (cont.)
Lockheed Martin	Nicholas Ricciardi
Northwest Energy Efficiency Council	Melanie Danuser
Northwest Power and Conservation Council	Kevin Smit
Pacific Gas & Electric	Patrick Moore
PacifiCorp	Nancy Goddard
Ptarmigan Consulting/ RTF	Christian Douglass
PUD No. 1 of Chelan County	Jim White
Puget Sound Energy	Chao Chen
Seattle City Light	John Owen
Seattle City Light	Lucie Huang
Snohomish County PUD	Allison Grinczel
Snohomish County PUD	Jim Conlan
Snohomish County PUD	Rick Rosenkilde
Taco Comfort Solutions	Mark Chaffee
Tacoma Public Utilities	Matthew Walker
Xcel Energy	Shari Kelley

The TWG met 6 times over the course of the research, with engagement in all phases of the research, from research plan development through data collection, analysis, and reporting. The first meeting occurred on April 9th, 2018 and focused on reviewing the Research Plan. While the RTF Research Plans were the basis for this research, the research team discussed some deviations with the TWG to confirm that any changes were necessary and did not impact the outcome of the research. In each subsequent TWG meeting the research team presented the status of the project and solicited insight from TWG members on questions that arose or deviations from the original research design. This input became invaluable as the research team started collecting data and determined that adjustments to the sample strata and applications established in the original RTF Research Plans were required (these changes are discussed in Section 4.2.3 for Clean Water Pumps and Section 5.2.3 for Circulators). The TWG was also pivotal in collecting data incorporated in this research. The time and resources the TWG dedicated to finding and submitting data and supporting the review process were instrumental to the success of this research.

The research team posted information from each Technical Work Group meeting on the XMP Conduit Website for external review and availability.[24] The team also posted important documents, such as the Research Plan, Data Submission Form, and data collection outreach materials. Feedback and review throughout the research was integral to the completion of this report and the research that is presented in Sections 4 and 0 (for Clean Water Pumps and Circulators, respectively).

[24] The XMP Conduit Webpage can be found at https://conduitnw.org/Pages/Community.aspx?rid=255#groupResourcesTab

4 Clean Water Pumps Research

This Section presents background, research questions, data collection process, and analysis results for Clean Water Pumps in the Northwest. Section 0 presents an analogous discussion for Circulators.

4.1 RTF Unit Energy Savings Measures

The RTF established Unit Energy Savings Measures for Clean Water Pumps during their meeting on December 6th, 2016. SBW Consulting was the primary contractor that developed the UES workbook and measures[25]. The measure review process included two Technical Sub-committee meetings and one Research & Evaluation Sub-committee Review. The measure utilizes a simplified energy consumption model and certain assumptions about the operation of pumps to establish energy savings estimates applicable at the point of sale. The measure identifiers determine the inputs to the energy savings equations and include the following:

- **Speed Control** identifies the speed control of the baseline pump and the efficient-case pump. There are three different Pump Speed Control combinations possible in the measure set:
  - Constant Speed → Constant Speed (CS->CS)
  - Variable Speed → Variable Speed (VS->VS)
  - Constant Speed → Variable Speed (CS->VS)
- **Pump Efficiency Level** is the increase in efficiency of the efficient-case pump from the baseline pump. PEI or ER is used as the identifier for Pump Efficiency Level. The measure set uses the difference between the rated PEI of the efficient-case pump and the average baseline PEI for the pump configuration. Baseline PEI is based on the pump type, speed control method, and motor horsepower (motor HP).
- **Motor HP** is the identifier used to determine the size of the pump. The measure development team considered pump horsepower as the measure identifier, but the motor HP was considered a less ambiguous value (pump horsepower is dependent on duty point, BEP, impeller trim) and more easily identifiable by distributors.
- **Pumping Application** determines the operating hours and load profile of the pump. The RTF analysis establishes three different applications:
  - Commercial HVAC
  - Agricultural Irrigation
  - Industrial Process Loads
- **Pump Class and Nominal Speed** refers to the definition established by DOE for the mechanical configuration of the pump, coupled with the nominal speed of the pump. The definitions for each pump class are in the Code of Federal Regulation (10 CFR 431.462) and include:
  - *End Suction Close Coupled (ESCC)* – "a close-coupled, dry rotor, end suction pump that has a shaft input power greater than or equal to 1 hp and less than or equal to 200 hp at BEP and full impeller diameter and that is not a dedicated-purpose pool pump. Examples

[25] SBW Consulting was funded by NEEA to develop these measures and received technical assistance from the RTF CAT and PNNL (Sarah Widder) in development of the measures, as well as pump manufacturers and industry subject matter experts through the Pump Subcommittee.

include, but are not limited to, pumps within the specified horsepower range that comply with ANSI/HI nomenclature OH7, as described in ANSI/HI 1.1-1.2-2014"

- *End Suction Frame Mounted (ESFM)* – "a mechanically-coupled, dry rotor, end suction pump that has a shaft input power greater than or equal to 1 hp and less than or equal to 200 hp at BEP and full impeller diameter and that is not a dedicated-purpose pool pump. Examples include, but are not limited to, pumps within the specified horsepower range that comply with ANSI/HI nomenclature OH0 and OH1, as described in ANSI/HI 1.1-1.2-2014"
- *In-Line* – "a pump that is either a twin-head pump or a single-stage, single-axis flow, dry rotor, rotodynamic pump that has a shaft input power greater than or equal to 1 hp and less than or equal to 200 hp at BEP and full impeller diameter, in which liquid is discharged through a volute in a plane perpendicular to the shaft. Such pumps do not include pumps that are mechanically coupled or close-coupled, have a pump power output that is less than or equal to 5 hp at BEP at full impeller diameter, and are distributed in commerce with a horizontal motor. Examples of in-line pumps include, but are not limited to, pumps within the specified horsepower range that comply with ANSI/HI nomenclature OH3, OH4, or OH5, as described in ANSI/HI 1.1-1.2-2014"
- *Radial Split, multi-stage, vertical, in-line diffuser casing (RSV)* – "a vertically suspended, multi-stage, single axis flow, dry rotor, rotodynamic pump:
    1. That has a shaft input power greater than or equal to 1 hp and less than or equal to 200 hp at BEP and full impeller diameter and at the number of stages required for testing and
    2. In which liquid is discharged in a place perpendicular to the impeller shaft; and
    3. For which each stage (or bowl) consists of an impeller and diffuser;
    4. For which no external part of such a pump is designed to be submerged in the pumped liquid; and
    5. Examples include, but are not limited to, pumps complying with ANSI/HI nomenclature VS8, as described in ANSI/HI 2.1-2.2-2014"
- *Submersible Turbine* – "a single-stage or multi-stage, dry rotor, rotodynamic pump that is designed to be operated with the motor and stage(s) fully submerged in the pumped liquid; that has a shaft input power greater than or equal to 1 hp and less than or equal to 200 hp at BEP and full impeller diameter and at the number of stages required for testing; and in which each stage of this pump consists of an impeller and diffuser, and liquid enters and exits each stage of the bare pump in a direction parallel to the impeller shaft. Examples include, but are not limited to, pumps within the specified horsepower range that comply with ANSI/HI nomenclature VS0, as described in ANSI/HI 2.1-2.2-2014"

The nominal speed of a pump is either 1,800 RPM or 3,600 RPM. A pump with a designed speed of rotation from 1,440 to 2,160 RPM is considered to have a nominal speed of 1,800 RPM, and a pump with a designed speed of rotation from 2,880 to 4,320 RPM is considered to have a nominal speed of 3,600 RPM (10 CFR Subpart Y, Appendix A, C.1.1).

The combinations of these measure identifiers produce a measure set that includes 3,336 individual UES estimates. Two main factors drive the energy savings mechanisms for these pumps: an increase in the efficiency in the pump (a change in PEI from the baseline to the efficient case) and the change in speed control of the motor changed from the baseline to the efficient case. The RTF created a simplified energy savings model to calculate the savings, relying on the measure identifiers to determine the model inputs for each unique UES estimate. The measure development team made assumptions to develop the model, which introduced uncertainty into the energy savings estimates and informed the development of the research questions addressed in this report.

4.1.1 Energy Savings Model

The RTF's energy savings model is based on the principle that energy savings are equal to the efficient case energy consumption subtracted from the baseline energy consumption, where the energy consumption of a pump is calculated as

$$Energy_{pump} = \boldsymbol{HP} * 0.746 * OpHrs_a * \boldsymbol{PEI} * AdjFactor_{p,c} \tag{6}$$

where

$Energy_{Pump}$	=	Energy consumed by the pump, in kWh
HP	=	The motor nameplate horsepower
$OpHrs$	=	Annual operating hours of the pump
PEI	=	Pump Energy Index
$AdjFactor$	=	An Adjustment Factor to correct for real-world operating characteristics
a	=	Pump application (commercial, industrial/municipal, or agricultural)
p	=	Pump class, based on the DOE pump class and nominal speed
c	=	Speed control of the pump system (constant speed/variable speed)

Using this simplified model, the RTF model calculates energy savings as:

$$Energy_{savings} = \boldsymbol{HP} * 0.746 * OpHrs * \left(PEI_{Base}AdjFactor_{base} - \boldsymbol{PEI_{Eff}}AdjFactor_{Eff}\right) \tag{7}$$

where

$Energy_{Savings}$	=	Energy savings, in kWh
HP	=	The motor nameplate horsepower
$OpHrs$	=	Annual operating hours of the pump
PEI_{base}	=	Pump Energy Index of the baseline pump
PEI_{Eff}	=	Pump Energy Index of the efficient case pump
$AdjFactor_{base}$	=	The Adjustment Factor (to correct for real-world operating characteristics) of the baseline pump
$AdjFactor_{eff}$	=	The Adjustment Factor (to correct for real-world operating characteristics) of the efficient case pump

As the equations reflect, this model relies on five key variables, two of which are inputs (**HP** and **PEI_{Eff},** shown in **bold**) and three of which are assumed based on the pump sector and pump class (OpHrs, Adjustment Factor, and PEI_{Base}). Motor HP is used to determine pump size and PEI is used as an indicator for relative efficiency. Both values are stamped on equipment nameplates (motor nameplate and pump nameplate, respectively), and can be determined at the point of sale. The operating hours are assumed based on the application in which the pump is installed, and Adjustment Factor is assumed based on the pump class. The PEI of the baseline pump also varies according to the pump class and application. The model assumes baseline PEI according to the current practice baseline pump. Section 4.1.2 outlines the values and related assumptions for each variable.

4.1.2 Assumptions and Research Questions

The RTF based its energy modeling assumptions mainly on DOE's analysis supporting the January 2016 Pumps Standard rulemaking (81 FR 4368 (Jan 26, 2016). The analyses presented in this report aim to improve the overall reliability of the energy savings estimates through improved reliability of the inputs to the savings equation. To this end, the team reviewed and addressed the RTF's specific assumptions for estimating Operating Hours, Adjustment Factor, and Baseline PEI.

4.1.2.1 Operating Hours

The planning measures assume operating hours are consistent within each sector. Table 11 shows the estimates that the RTF subcommittee established on for each sector.

Table 11: RTF Assumed Operating Hours

Sector	RTF OpHrs
Commercial HVAC and DHW	4,000
Industrial, including Municipal	5,000
Agricultural Irrigation	2,400

The Commercial Operating Hours estimates are based on information from DOE's Technical Support Document[26] and input from industry experts during the RTF's subcommittee meetings, supplemented by any available regional research. In addition to the DOE analysis, the RTF used the Northwest Motor Database[27] to determine the Industrial operating hours. Two sets of data from the Bonneville Power Administration's Agricultural Irrigation Programs[28] determined the Agricultural irrigation operating hours for the RTF estimates.

The analysis in this report includes a comparison of the observed operating hours, from collected operational data, to the RTF-assumed operating hours and underlying data sources. The observed operating hours will determine if more granularity in the measures estimated operating hours is justified to improve the accuracy and precision of the measures.

4.1.2.2 Adjustment Factor

The RTF empirically derived the Adjustment Factor using DOE's Life Cycle Cost Analysis (LCC) Sample. They modified the LCC Sample to model the energy use of 219 pumps operating at various duty points and load profiles. Equation 8 shows the calculation for Adjustment factor,

$$AdjFactor = \frac{Average\ Simulated\ Pump\ Curve\ Energy}{HP * 0.746 * OpHrs * PEI} \quad (8)$$

---

[26] While the RTF Measures only include 3 applications, DOE's LCC analysis provides operating hour ranges for 5 applications (Cooling Water, Boiler Feed, Circulation, Pressure Boost, Irrigation, Other (US DOE 2015)).

[27] The Northwest Motor Database is a collection of over 22,000 records of energy audits on motors, collected over a 20-year period covering small and medium size facilities. Not all the motors in the NW Motor Database are attached to pumps, and of the motors that are attached to pumps not all fall within the motor HP range addressed in the RTF Measures, so the RTF used the records that met the criteria of the measures.

[28] Bonneville Power Administration's data is presented as the average annual operating hours, separated into seven different buckets ranging from 5 HP to 5000 HP. To develop the operating hour estimate for the agricultural sector the RTF calculated the average of the annual operating hours for pump in the buckets from 5 HP to 200 HP.

where:

$Average\ Simulated$ $Pump\ Curve\ Energy$	=	The energy use modeled in the modified LCC Sample
HP	=	Motor HP
OpHrs	=	Operating Hours of the pump
PEI	=	Pump Energy Index

The energy savings model uses Adjustment Factor to account for differences between theoretical pump operation (accounted for in PEI) and actual pump operation. This research collected operational information from pumps operating in the field and determined observed annual energy use. The research team then re-calculated Adjustment factor using observed energy use to determine the validity of the Adjustment Factor developed based on the LCC Sample.

To investigate the source of differences in Adjustment Factor among pump sectors, applications, and speed control cases the research team collected data on the key drivers of Adjustment Factor: Load Profile, Motor Oversizing, and BEP Offset.

Load Profile refers to the amount of time, as a percent of annual operating hours, the pump operates at various percentages of flow at BEP. The RTF's calculation of Adjustment Factor relied on the load profiles developed by DOE in its rulemaking analysis. DOE established 4 load profiles for their analysis of constant speed pumps, and a probability distribution between them. DOE then adjusted these load profiles to represent variable-speed pump operation, which created an energy savings due to VFD-addition of 29% (39% due to VFD, with an effectiveness rate of 75%).

The RTF used the same constant-speed pump load profiles for the calculation of Adjustment Factor. They calibrated the variable-speed pump load profiles to achieve 29% savings at 20% minimum head.

This research determined the load profile for the samples collected and compared them to the load profiles included in the RTF's calculation of Adjustment Factor. The research team also investigated the impact load profile has on the Adjustment Factor.

Motor Oversizing refers to the assumption that motor nameplate horsepower is 120% of pump horsepower. The energy savings model employs motor nameplate horsepower, as opposed to pump horsepower, because the RTF analysis team felt it would be a more reliably known value. Pump Horsepower more accurately describes pump operation but is dependent on factors like duty point, BEP, and impeller trim. In order to use motor HP, the subcommittee assumed that the motor HP was 120% of the pump horsepower at BEP, based on the same assumption in the DOE Pumps Test Procedure and Standards rulemaking analyses.

To investigate the validity of this assumption this research compares the motor HP to the pump power at BEP to determine if 120% motor oversizing is a reliable estimate.

The research plan divides the range of motor HP's into 4 strata and aims to recruit from each stratum equally. The motor HP range for this research is from 1 – 200 motor HP. NEEA will address any information on the distribution of HP within different sectors in their market research. Beyond the validation of the motor oversizing estimate motor HP was used as a sensitivity variable, and the research team investigated any differences in operating hours and Adjustment Factor within applications and across motor HP Bins.

BEP Offset is the variation in where the system curve intersects the pump curve, or the difference between BEP and actual operating point. Best Efficiency Point is the point on the pump curve where the efficiency of the pump is highest. The Adjustment Factor calculation uses DOE's LCC assumption of -25% to +10% of BEP. The BEP Offset varies based on pump sizing and selection practices and was expected to be dependent on the speed control method, because of the likelihood of pump oversizing with variable speed pumps. The team used the operational data they collected to evaluate the variance in BEP offset compared to the assumption made by the RTF.

Static head is the minimum amount of pressure the pump must overcome to start moving water through the system. In the development of the LCC Sample DOE used a static head value equal to 20% of head at BEP. The static head set for the system curve by DOE's Test Procedure is 20% of head at BEP (**Citation)**. The RTF subcommittee proposed different static head values for each pumping application. These static head values are listed in Table 12. The subcommittee decided that Industrial and Municipal and Agricultural Irrigation were well represented with a static head set at 20% of head at BEP, but adjusted the Commercial HVAC and DHW to be 40% of head at BEP.

Table 12: Static Head by Pumping Application

Pumping Application	Minimum Head (% of head at BEP)
Commercial HVAC and DHW	40%
Industrial and Municipal	20%
Agricultural Irrigation	20%

4.1.2.3 Baseline PEI

Baseline PEI represents the market average pump efficiency in the baseline case (i.e., in the absence of programs). The baseline PEI is calculated separately for each of DOE's pump classes and the different speed control cases (constant speed or variable speed). Shipments estimates from DOE's TSD inform the calculation of constant speed baseline PEI. Variable speed baseline PEI adjusts the constant speed estimates using DOE's test procedure for calculating the PEI of a pump retrofitted with a drive. This study does not focus on evaluating the baseline PEI. However, NEEA is pursuing parallel market research that will help improve or corroborate the measure assumptions related to the baseline PEI for different measure applications.

4.2 Data Collection Methodology

To validate the energy savings estimates and support the RTF measure workbooks' assumptions, the research team needed to know how pumps operate in the Northwest. Furthermore, the team needed to know how and where those pumps are installed in order to validate the aggregation that was established in the measures. The team designed the research to collect two different types of information to meet these needs: audit data and operational data.

Audit Data is related to the pump and pumping system characteristics and installation configuration. It includes information regarding pump type, size, speed, and design operating point, as well as information on the installation characteristics of the pump, like the speed control method, the presence of a redundant pump, and the drive installation method (if applicable).

Operational Data is logged, real-time information on how the pump operates. This can include information on the flow through the system, the power draw from the pump, the speed at which the VFD is operating, and the pressure at which the system is operating. Logging equipment usually collects operational data at a discrete time interval (e.g., every 5 minutes), but sometimes log data on a "change of value" basis, where the data logger records when the value of a variable changes. Logging equipment uses the latter method of data recording when there are a finite number of possible values for the variable (for example, "change of value" data collection is common for collecting on/off data for a pump since there are only to possible values to record and small fluctuations in system pressure or flow will not register as noise in the logged data).

The research team collected data over the course of ten months. The outreach leveraged the existing networks of members of the research team and TWG to maximize the number of potential data contributors contacted. The research team reached out to various people and organizations that had access to pumps or metered pump data including Utilities, Implementors, engineering firms, and building management companies.

4.2.1 Data Sources

The team designed the research to utilize two different categories of data: existing pump data and primary (newly metered) pump data.

4.2.1.1 Existing Data

Existing data refers to operational data collected or logged for some purpose other than supporting this research. Common sources of existing data included custom Utility Pump Program documentation (which typically includes pre-post metering) or trend data from Building Automation Systems. Building Management Systems and Process Operation Systems monitor and log information like pump speed, flow rates, motor power draw. These systems collect data to indirectly control the pumps through monitoring their operation, but such data can be used to evaluate the energy consumption and annual operating hours of the system. The team designed the pump sample to be filled mainly through existing data, with a smaller portion of the sample from Primary Data. Utilizing existing pump data allowed the research team to maximize the number of pumps included in the sample by reducing the amount of budget spent on metering.

4.2.1.2 Primary Data

Newly metered pump data, or "primary data", is pump operational data metered with the primary purpose of supporting this research. The research team planned to use primary data both to corroborate the findings from existing data collection and to bolster the sample where existing data was insufficient. The sample collected is made up of a smaller percentage of primary data vs existing data. Leveraging both categories of data allowed the research to utilize outreach resources as effectively as possible, maximize the sample size for each application, and fill the established sample strata.

4.2.2 Sample Strata

The Research Strategy published by the RTF for Clean Water Pumps proposed sample sizes for different applications. Table 13 shows the sample sizes proposed by the Research Strategy.

Table 13: RTF Proposed Sample Sizes for Data Collection

Application	Operating Hours	Pump System Energy Consumption		
		CS→CS	VS→VS	CS→VS
Commercial: condenser and cooling tower	30	10	15	15
Commercial: chilled water loops	30	10	15	15
Commercial: heating	30	10	15	15
Commercial: domestic hot water circulation	30	10	15	15
Commercial: pressure boost	30	10	15	15
Industrial	30	20	30	30
Agricultural irrigation	30	10	15	15
Municipal water distribution/treatment	30	10	15	15
Totals	**240**	**90**	**135**	**135**

The RTF used a sample of 80 pumps in the Commercial HVAC applications (specifically Chilled Water Pumping and Condenser Water Pumping) to establish these targets. The RTF subcommittee decided to apply the same sample size across all applications included in the research. The exception to this is the "Industrial" Application, for which the research strategy targets a larger sample size. Although the RTF research plan does not specifically state the reasoning behind the larger "Industrial" application sample, the broad range of sub-applications that fall into "Industrial" would seem to predicate a need for a larger sample size.

The research team used the proposed sample sizes shown in Table 13 as the data collection target, with the understanding that the RTF specifically noted researchers should "scrutinize both the sample targets within each application and the application types definitions themselves", (RTF 2016). The research established goals for the number of samples collected through Primary Data Collection and the number of samples collected through Existing Data Collection. Table 14 shows the breakdown of the total sample target by data collection method.

Table 14: Data Collection Targets, Newly Metered Samples and Existing Data Samples

Application	Newly Metered Sample	Existing Data Sample	Total Samples
Commercial: Condenser and Cooling Tower	3	32	35
Commercial Chilled Water Loops	3	32	35
Commercial: Heating	3	32	35
Commercial Domestic Hot Water Circulation	3	32	35
Commercial Pressure Boost	3	32	35
Industrial	5	75	80
Agricultural Irrigation	--	35	35
Municipal Water Distribution/Treatment	3	32	35
Totals	**23**	**302**	**325**

As data collection progressed, the research team made modifications to the sampling plan that reflected factors like real-world pump application, data availability, and practicality.

4.2.3 Data Collection Outcomes

Over the course of ten months of outreach the research team collected and analyzed a total of 399 Clean Water Pumps into the database. Over the course of the data collection, the applications laid out by the RTF and the target sample sizes established we reviewed multiple times, and adjustments were made to allow for better characterization of pumping applications and to account for aspects of the pump stock in the Northwest.

The research team started outreach in August 2018 with the RTF's sample strata as a guide for outreach and data collection. The team held two high-level Stage Gate meetings in November 2018 and February 2019 to review the data that had been collected to date in each application, gather input on successful outreach, discuss any observed issues in each application, and make any necessary modifications to the definition or targets within any of the application sample strata. The research team reviewed these changes with the Technical Work Group prior to updating the application targets and application definitions. The subsequent sections detail these and other, more nuanced changes made to the final sample.

4.2.3.1 Changes in Speed Control Targets

Through the data outreach and collection, the research team found it increasingly hard to find existing data from constant speed pumps. At the first stage gate meeting it was discussed that there were two probable reasons for this: (1) when people think about increasing the efficiency of a pump the most often think of a the addition of a VFD, which led people to send information on pumps that had VFDs attached, and (2) pumps on control systems that monitor and collect the information the research team was requesting are usually more advanced, and the VFD was another point from which operational data could be retrieved. In addition, the team observed that the RTF set the initial targets based on limited analysis of primarily variable speed commercial HVAC pumps, which would potentially have much more variable operating profiles than constant speed pumps. As such, the team proposed, and the TWG agreed, to reduce the constant speed sample target to 5.

Through the data collection process, the research team saw was a lack of data in the constant speed -> variable speed control case (i.e., variable speed with constant speed baseline). In this sample strata, the team is targeting retrofit projects where both baseline constant speed and post-retrofit variable speed data are available. The main reason for this lack of data is that while data for the other two control cases can be found in multiple different existing sources, CS -> VS data can only be found from utility pump improvement projects which greatly decreased the pool of data that could be leveraged. To address this issue, the team proposed to collapse the variable speed control cases into one case, instead of two with different baseline control cases. The team acknowledges that this change limit how much the research can evaluate whether or not there are any notable differences in the average load profile or operating characteristics of variable speed pumps with variable speed baselines versus those with constant speed baselines. However, the team believes, and the TWG agreed, that the research will still collect good a robust data on the operating characteristics of variable speed pumps in general, which should be sufficient to verify the RTF measures.

4.2.3.2 Application-Specific Targets

The research team, in consultation with the TWG, also defined and made changes to the application specific sample targets, especially in applications where the team was struggling to recruit sample. At the 5th Technical Work Group Meeting the team presented the data that had been collected to date and determined that the data that had been collected met the requirements for individual applications, as discussed below.

4.2.3.2.1 Commercial Condenser/Cooling Tower

The RTF Measure Workbook and the RTF Research Plan do not explicitly define the applications. When reviewing each application, the research team defined the “Condenser/Cooling Tower” application as pertaining to open, recirculating cooling systems that utilize flow over media to either decrease the temperature of the water used in the cooling system or decrease the temperature of a coolant piped through the media. This definition ostensibly refers to evaporative condensers and cooling towers and the research team felt the term “Cooling Tower” simplified the application name and removed ambiguity in the definition of “condenser”.

Table 15 shows the number of pumps collected in the Commercial Cooling Tower Application. Only 2 constant speed pumps were collected, but the research team felt that with all of the pumps collected through primary data collection and a large sample of variable speed pumps, 2 was a suitable sample for constant speed in this control case.

Table 15: Pumps identified in Commercial Cooling Tower Application

	Operating Hours	Constant Speed	Variable Speed
Existing Data	35	0	35
Primary Data	3	2	1
Total	38	2	35

4.2.3.2.2 Commercial Chilled Water Loop

The label "Chilled Water Loop" is clear and concise, but it resulted in a lot of questions on what exactly qualified as a "Chilled Water Loop". The team decided that changing this application to simply "Cooling" broadened the applicability of the label and, when viewed in conjunction with the "Cooling Tower" application, implied a closed-cooling loop.

Table 16 shows the number of pumps identified in the Commercial Cooling Application. With 6/10 Constant speed pumps collected, and all through primary data, the research team felt 6 pumps a sufficient sample.

Table 16: Pumps identified in Commercial Cooling Application

	Operating Hours	Constant Speed	Variable Speed
Existing Data	73	0	73
Primary Data	11	6	5
Total	84	6	78

4.2.3.2.3 Commercial Heating

The application label "Heating" was not changed, and it was established that it referred to water source heat pump Heating Loops, boiler hot water pumps to Air Handler Unit coils, or any other closed heating loop.

Table 17 shows the number of pumps that were identified in the Commercial Heating Application.

Table 17: Pumps identified in the Commercial Heating Application

	Operating Hours	Constant Speed	Variable Speed
Existing Data	16	6	10
Primary Data	8	4	4
Total	24	10	14

4.2.3.2.4 Commercial Pressure Boost

The application "Pressure Boost" was clear and concise and the research team felt it accurately described the application. The inherent nature of pressure boosting is that the pumps are all serving the exact same purpose, with very little variation in operation within this application. With this in mind the research team felt that the 20 pumps identified for Commercial Pressure Boost, evenly split between constant and variable speed as shown in Table 18, are adequate to represent the application. This especially true, since Pressure Boost is expected to be a fairly consistent application, since it is not weather dependent.

Table 18: Pumps identified in the Commercial Pressure Boost Application

	Operating Hours	Constant Speed	Variable Speed
Existing Data	7	3	4
Primary Data	13	7	6
Total	20	10	10

4.2.3.2.5 Commercial Domestic Hot Water Circulation

Over the course of data collection the research team determined that in almost no circumstances is this application served by Clean Water Pumps, which are, by definition, limited to pumps larger than 1 motor HP.[29] This is an application that is served by Circulators, as very few buildings in the Northwest are large enough to demand a pump larger than a Circulator. Table 19 shows that the research team was only able to identify two Commercial DHW systems served by Clean Water Pumps, and because of this the research team decided to eliminate this as an application in the Clean Water Pumps research and use the information that was collected from the two Clean Water Pumps to characterize Circulators operating in the commercial DHW application in the circulator research. The Circulator sample strata and research design are discussed further in Section 0.

Table 19: Pumps identified in the Commercial Domestic Hot Water Circulation Application

	Operating Hours	Constant Speed	Variable Speed
Existing Data	0	0	0
Primary Data	2	2	0
Total	2	2	0

4.2.3.2.6 Agricultural Irrigation

The data collected for agricultural irrigation is in a slightly different format than the data collected for the other applications. The audit data is the same, but where the other applications had hourly or sub-hourly data submitted over the course of a timeframe shorter than 12 months, the agricultural operational data was submitted as either monthly or yearly operational hours and energy consumption spanning an entire operating season. Not all pumps were submitted with both operating hours and energy consumption, which can be seen in Table 20.

Table 20: Pumps identified in the Agricultural Irrigation Application

	Operating Hours	Constant Speed	Variable Speed
Existing Data	139	30	12
Primary Data	-	-	-
Total	139	30	12

4.2.3.2.7 Municipal Water Treatment/Conveyance

The data collection highlighted that the majority of the pumps in this application are larger than 200 motor HP. Through conversations with data submitters and the process of identifying pumps there were often a large number of pumps, but only a few fell under the motor HP size limit. Table 21 shows that the targets for data collection were met in this application.

[29] As noted previously, the DOE regulations and RTF measure applications define Clean Water Pumps as pumps between 1 and 200 hp. 10 CFR 431.464 and 465.

Table 21: Pumps identified in the Municipal Water Treatment/Conveyance Application

	Operating Hours	Constant Speed	Variable Speed
Existing Data	39	13	26
Primary Data	0	0	0
Total	39	13	26

4.2.3.2.8 Industrial

As the team undertook outreach to industrial pump owners/operators it became evident that the application of "Industrial" was too broad an application. Through conversations with pump owners and the experience of the team the consensus was that there are too many "sub-applications" within the industrial sector where pump operation is dependent on factors like the industry being served, the type of product being produced, where in the chain of production the facility falls to adequately and confidently characterize "Industrial pumps". With this understanding the team established two Industrial applications that are likely to operate more consistently across multiple industries and in multiple types of facilities and therefore, be easier to characterize and include as a deemed measure. These two industrial applications are "Cooling Pump" and "Boiler Feedwater Pump". Pump data was collected before the Stage Gate Meeting that do not fall into these two applications, and they are labeled "General Industrial Pumps".

Table 22, Table 23, and Table 24 show the pumps that were identified for each Industrial Application. The research team did not have enough information on the applications to establish speed control targets but aimed to collect 15 pumps in each application. BFW was the only application that the target was not met, with only 13 pumps identified.

Table 22: Pumps identified in the Industrial General Application

	Operating Hours	Constant Speed	Variable Speed
Existing Data	9	7	2
Primary Data	5	5	0
Total	14	12	2

Table 23: Pumps identified in the Industrial BFW Application

	Operating Hours	Constant Speed	Variable Speed
Existing Data	2	1	1
Primary Data	11	10	1
Total	13	11	2

Table 24: Pumps identified in the Industrial Cooling Application

	Operating Hours	Constant Speed	Variable Speed
Existing Data	23	7	16
Primary Data	19	14	5
Total	42	21	21

Table 25 shows the final disposition of the data collection, with the adjusted, application-specific targets. The totals in this table do not represent the total number of pumps collected, but the total number of pumps up until the application strata was filled (e.g., 38 pumps were collected for Commercial Cooling Tower Operating Hours, but only 30 of those pumps are included in the total). In each of these final sample strata, the research team also reviewed the collected pumps to ensure a representative range of HPs, building sites, and geographic locations were included.

Table 25: Final Sample Strata with Adjusted Targets

Application	Operating Hours	Pump System Energy Consumption	
		Constant Speed	Variable Speed
Commercial: Cooling Tower	38/30	2/5	35/20
Commercial: Cooling	84/30	6/9	78/15
Commercial: Heating	24/30	10/10	14/15
Commercial: Pressure Boost	20/23	10/10	10/12
Industrial: Cooling	42/15	21/10	21/8
Industrial: Boiler Feedwater	13/13	11/10	2/0
Agricultural: Irrigation	139/30	30/10	12/12
Municipal Water Distribution	39/30	13/10	26/15
Sample Frame Totals	**199/201**	**68/74**	**95/97**
Total Pumps Collected	**399**	**103**	**198**

4.2.4 Data Standardization and Annualization

The operational data submitted took various forms; with the units used for each variable, the way each variable was determined, and the timeframe of data submitted varying between data contributors.

To help address this variability, the research used a "Data Submission Form" to collect the audit and operational data. Included in Appendix B, the Data Submission Form is an excel tool that worked to standardize the responses and decreasing the burden on the research team to decipher different terminology that can be used to describe similar pump characteristics. Multiple different data sources were used when collecting information for this research, which made the need for a standardized data format paramount.

To ensure all audit data and operational data was accurate and correct, the team implemented a rigorous QAQC process to check all submitted data for any inconsistencies or errors. This QAQC process was developed separately for the audit data, as well as the operational data, and are described in detail in the following Sections.

It was also necessary for the research team to further standardize the operational data to complete the analysis. However, transparency of analysis and a traceable chain of custody for the data is critical to ensuring understanding and confidence in the results. To achieve both these goals a data quality control process was developed that tracked the process of data collection, standardization, and annualization. This process resulted in standardized audit data and three operational data tables in the final database: the Raw Operational Data Table, the Aggregated Operational Data Table, and the Annualized Operational Data Table. This Section lays out the QAQC Process for audit data and operational data at a high level, along with method of data annulation. The detailed process flow diagram and step-by step method of QAQC is presented in the Data Management Plan in Appendix A.

4.2.4.1 Audit Data Collection and QAQC Process

Audit data was submitted to the research using the Data Submission Form. This template is excel-based and organizes the audit data into 3 sections: Data Contributor Information, Required Pump Information, and Optional Pump Information.

Data Contributor Information is information on the person and organization submitting the information. This section is included in the template to ensure the research team can reach out to the contributor if there is an issue with the submission or there is a question/incongruity in the information submitted. This information remains private, *is not entered into the database, and is not disclosed to any party outside the research and research team.*

Required Pump Information is information that is needed to include the pump in all facets of the analysis. The information in this section includes pump nameplate and motor nameplate information, application and installation information, and speed control method information. Pumps were submitted to the research that did not have complete information in this section. If all the required pump information was not included the pump was not rejected, however it was only included in portions of the analysis that the information was present for (e.g., if there was not enough information submitted to determine PEI the pump was not able to be included in the analysis of Adjustment Factor, but was included in the analysis for Operating Hours)

Optional Pump Information includes data on the vintage of the pump, the drive installation type, and how the pump was installed in relation to the commissioning of the system (e.g., was the pump installed when the system was commissioned or is it a pump that replaced an original pump). These data are useful for additional analyses outside the primary research questions discussed in Section 4.1.2. Table 26 lists the audit data that is collected and the reason/purpose for collection. For a detailed list of audit information that was collected please refer to the Data Submission Form.

Table 26: Audit Information and purpose for collection, Clean Water Pumps

Audit Data	Justification/Purpose
Required Pump Information	
Pump Nameplate Information	Allows for the pump curve to be located and provides information on actual operation vs rated operation (e.g., impeller trim)
Motor Nameplate Information	Provides Motor HP as well as information to calculate PEI
Sector and Application	Allows the research team to determine if operating characteristics are dependent on the application
Pump Control	To determine how measured flow should be interpreted For constant speed, typical options include: throttling valve or bypass. For variable speed, typical options include: variable speed drive or multi-speed motor. If pump control has its own nameplate information, it will be recorded.
Optional Pump Information	

Audit Data	Justification/Purpose
Pump Redundancy Role	To determine how measured operating hours should be interpreted and applied
Pump Installation Method	Allows for the potential to explore pump performance of original vs. retrofitted pumps
Pump Static Head	To determine application system curve and pump minimum turndown ratio
Continuous Controls Installation Method	To determine if pump performance varies based on manufacturer- vs distributor- or site-paired systems

The audit information provided was used to find the pump performance curve for each specific pump. These performance curves were used to determine pump performance information, such as flow and head at BEP, empirically calculated pump performance curves, and to calculate PEI. Specifically, for each pump model, the flow (in gpm), head (in feet), and efficiency are determined at six points on the pump performance curve. These values are entered into the "Literature Values" section of the Data Submission Form and used to derive additional pump performance parameters as described in more detail in the Data Management Plan.

After this analysis is complete, the Audit Data QAQC Checklist is performed by the research team. This QAQC checklist has the data-checker walk through the information that was submitted, ensure it is formatted correctly (e.g., units are not included in "value" cells, notes are entered when "Other" is selected as the response), ensure the information is consistent with any information that was received previously (either in different data submissions or through discussions between the data submitter and the research team), and make sure there are not contradicting each other (e.g., a pump is listed as having multiple stages when the Pump Class cannot have multiple stages, an application is chosen that does not exist in the chosen sector).

The Data Submission Form is formatted to be as explicit and straight-forward as possible. One aspect of data collection that this research aimed to avoid is multiple different ways to describe the same process (e.g., when asked to describe the same object 10 people will describe it 10 different ways). To mitigate this all entry cells that can be are "discrete answer cells", or "drop down menus" that provide a list of the possible answers. This reduced the burden of cross-checking the information submitted with the format of the research but did not eliminate it. When a cell needed to be changed to match the acceptable format, or "Other" was chosen when it should not have been, the data submitter was contacted and the change was confirmed.

Once the Audit Data QAQC Checklist is complete the audit data is uploaded to the database. The database is automated to calculate PEI in accordance with the calculation-based approaches provided in DOE's Test Procedure for Pumps (10 CFR 431; Appendix A to Subpart Y, sections III, V, and VII) using the pump performance parameters derived from the audit information provided by the data submitter and the literature values entered into the Data Submission Form by the research team. For pumps where the manufacturer-rated PEI is available[30] the calculated PEI is compared to the manufacturer-rated PEI. This

[30] Pumps are not required to be rated with PEI until the federal standard goes into effect on January 27th, 2020. Some pump manufacturers are already rating and labeling their pumps with PEI, which provides the opportunity for a comparison between the calculated and tested PEI in some cases.

allows for the analysis to account for any difference between the calculated PEI and the manufacturer-rated PEI.

4.2.4.2 Operational Data Collection and QAQC Process

Operational data is much more variable in regards to the format that it can be submitted in. Because the research is designed to leverage data collected previously as much as possible, the initial purpose for data collection varies, which means the exact data and format of that data is dependent on the method of data collection and the purpose for which it was originally collected. An example of this would be the collection of data from a digital control system (e.g., BAS, BMS, DDC, DCS, etc.) is dependent on how the control system was programed to store the data (e.g., stored as binary data with conversion values provided, stored as actual measurements, specific units used to measure the data, etc.), the time interval and type of data established by the system (e.g., 15 minute interval, logging instantaneous vs aggregate vs cumulative measurements), and the method the control system outputs reports (e.g., as a .csv file, as an excel table, in a PDF document, etc.). This variability necessitated the development of a multi-level QAQC Process. This process stores operational data in the database in three different forms: Raw Operational Data, Standardized Operational Data, and Annualized Operational Data, with a specific QAQC Process for each type of data.

4.2.4.2.1 Raw Operational Data

The Raw Operational Data stored in the database is simply the information that was submitted to the research formatted to be uploaded to the database. The information is taken from whatever format it was submitted in (e.g., csv file, pdf, etc.) and entered into the Data Submission Form with the time stamp to the left of all the operational data submitted. Each operational variable that can be submitted has a column available for the values with a corresponding column for the units the variable was submitted with. The submitted data is entered into this format and uploaded to the database. The QAQC for this data is minimal, and mainly includes reaching out to the data submitter to answer any questions on the submittal. The QAQC is minimal at this step because the purpose of the Raw Data Table is to present the information that was submitted to the research without any manipulation.

Once this information has been uploaded to the database a QAQC report is published, which presents a summary of the information that was submitted, including data ranges, averages, and plots the data submitted, both as time-series plots and in relation to other variables. This allows the QAQC team to identify any outliers, ensure the information that was submitted aligns with other variables, and clean the data submitted. If outliers or errors are identified they are noted, the issue is addressed, and the report is re-published for review. This process is iterative, ending when the research team has determined there are no issues in the data.

4.2.4.2.2 Standardized Operation Data

Any issues identified in the Raw Operational Data are addressed (i.e., the data is cleaned) and then the data is standardized[31]. The standardization process formats the information so it can be manipulated in the database. With multiple possible units that the data can be submitted in, multiple different time intervals that data could be collected in, and multiple combinations of operational variables that could be submitted it is necessary to format all operational data for all pumps the same.

---

[31] The data raw operational data table does not contain the cleaned data. The data is cleaned after it is uploaded to the raw operational database.

The units for all the submitted data are converted to standardized units for all pumps. Flow is standardized to gallons per minute (gpm), speed is standardized to revolutions per minute (RPM), power is standardized to kilowatts (kW), and differential pressure is standardized to feet of head (ft). In addition, at this step, any variables that are not provided directly in the raw data are calculated based on the pump performance information derived from the audit data (see Section 4.2.4.1).

Once the units are standardized and any missing data are derived based on the submitted data, the time stamp is aggregated to a 1-hour time stamp. The final output of operational data is 8760 instances of 1-hour operational data representing 1-year of operation. The aggregation process analyzes the submitted data and, if the submitted data is sub-hourly, averages all data points within the hour. If the next time stamp is greater than one hour in the future that point is assumed to be the last in that hour and the next hour is not calculated. This creates a data set that consists of 1-hour interval data with gaps where any data is missing, that only extends the duration of the data submitted. A state variable is generated through this process, which is a value from zero to one, representing the fraction of each standardized hour that the pump was operating.

A QAQC Report is published using this data and it is reviewed. This is to ensure the unit conversions and calculations were executed correctly, as well as catch any issues that were not seen in the initial QAQC Report. Once it is confirmed that the data is standardized correctly it is uploaded to the database.

4.2.4.3 Data Annualization Process

A hallmark of using previously collected data is the variability in the timeframe of data. In some cases a full year of operational data was collected (this is usually when information is downloaded from a control system or submitted from a long-term monitoring project), but in other instances the data submitted spans less than one year (it is common practice for Utility custom projects to monitor two-weeks of operation pre- and post-project). With this variability present the submitted data sets, the research team developed a consistent process for annualizing the data, using the information from the time frame submitted, to represent a year of operation.

Data from 10 applications is incorporated into the research. For each application the research plan outlines an ideal amount of data needed to accurately estimate annual pump performance, shown in Table 27. If all the pumps incorporated into the research had met the minimum collection timeframe established a basic annualization process could have been used, which would have extrapolated the data submitted to represent one year, and then been weather normalized.

Table 27: Minimum collection timeframes established by Research Plan

Application	Seasonal Effects on Operation	Collection Period	Minimum Collection Timeframe
Commercial: Condenser and Cooling Tower	Operating hours and load profile will vary based on A/C demand, which changes with outdoor temperature.	Winter*, Summer, & 1 Shoulder Season	6 weeks minimum (2 weeks in each month)
Commercial: Chilled Water Loops	Operating hours and load profile will vary based on A/C demand, which changes with outdoor temperature.	Winter*, Summer, & 1 Shoulder Season	6 weeks minimum (2 weeks in each month)
Commercial: Heating	Operating hours vary based on demand for heating, which will vary throughout the year.	Winter, Summer*, & 1 Shoulder Season	6 weeks minimum (2 weeks in each month)
Commercial: Domestic Hot Water Circulation	Operating hours will vary on occupancy Load profile will depend on water main temperature	July – December	2 weeks (minimum), with interview of facility staff**
Commercial Pressure Boost	Dependent on system size and pressure of water supply, which shouldn't be time-of-year dependent	April, July, October, January	2 weeks in each season
Agricultural Irrigation	Only in use during the growing season. Varies throughout the growing season, as shown in models of irrigation rates in Northwest	April - July	2 weeks – 1 month***
Industrial General **Industrial Cooling** **Industrial BFW**	Each industry will experience different high-volume periods and low volume periods. Each water type (process, cooling, etc.) will have specific load profiles	12 months	Dependent on conversation with facility operations team
Municipal Water Distribution/Treatment	Operating hours based on water use, which increases in the summer due to lawn and garden irrigation.	April, July, October, January	2 weeks in each season

Unfortunately, the sources that the research collected data from sometimes did not collect operational data for the timeframes outlined in Table 27. Especially with Utility Custom Pump Programs it is almost unheard of for more than two weeks of data to be collected. The research team took this limitation into account, and developed a robust method of data annualization, which accounted for the fact that data with a timeframe of just two weeks may be submitted. The research team developed a method to annualize the operation data that accounts for three different levels of temporal patterns: diurnal, weekly, and monthly/seasonally. The annualization approach also varies based on the pump application and known or expected operational dependencies.[32]

For all pumps, the annualization process creates two independent models to describe each pump submitted. The first model forecasts the probability of the pump operating at any given hour of the day. Depending on the known operating characteristic of each pump, this model may simply show constant operation, a cyclic schedule of operation, or a logistic regression estimating the probability of being on. The second model estimates the flow through the pump when the pump is operating. For some pumps, this is a constant flow (not necessarily dependent on speed control method), but for most, it is estimated using a linear regression model. Each model has four components:

Model Targets: For each model, we fit parameters to minimize the differences between a model estimate and a target variable that needs to be predicted.
Model Inputs: This are the values derived from the data provided that the models will utilize to make predictions.
Model Framework: The model framework describes how the two separate models interact with each other and the submitted data
Stochastic Simulation: In order to capture variability observed in the data, we simulate final operational estimates based on the outputs of the model.

Each of these model components are discussed in more detail in the following sections.

4.2.4.3.1 Model Targets

This process uses two predictive models in conjunction to generate normal annualized operational data. The first model estimates the likelihood of a pump being on at any given hour. The target variable selected for this model is a binary indicator, representing the state (on or off) of the pump during the majority of the most recent hour-long period. In the standardized tables state data is reported as the fraction of the hour the pump was operating. The annualization (and subsequent analyses) are conducted on an hourly level, so this process rounds all partial state values in the standardized table to either 0 or 1 to represent the general operational state of the pump for that hour, calculated as

$$T_i = round(State_i) \tag{9}$$

where

T_i = Operating state of pump (on/off)
$State$ = Standardized data pump operating value
i = Specific data instance

There are a handful of pumps that always operated for less than the full hour. In these circumstances, a random number generator is used to calculated a value between 0 and 1 and the Operating state T_i

[32] Through the data collection process the research team inquired about any known operating patterns/schedules that affected the pump operation. When available the annualization included pump-specific schedule information.

reflects whether the random number is smaller than the fractional state (thus if a pump operated as 0.25 for 24 hours, the process would be expected to a target operation of 6 out of 24 hours.

The second model estimates the flow of the pump for each hour the state variable establishes the pump as operating. The value of the flow variable in the Standardized Operational Data Table serves as the dependent variable for the regression model, with the population of the data used to train the model only including data points where the pump was operating.

4.2.4.3.2 Model Inputs

The model uses timestamp and local temperatures as predictors for the regression model. The model develops temperature-based inputs, lagged temperature-based inputs, and time-based inputs.

Temperature based inputs

The four temperature-based inputs developed for the model are:

Temperature - This is the outdoor ambient temperature taken from the nearest NOAA weather station.

IsWarm - This the balance point indicator, a binary indication of whether the temperature is above 65° Fahrenheit[33]

HxT - An interaction between the temperature and the balance point indicator, isWarm. HxT is the number of degrees this hour's measured temperature is below 65° F. The value is 0 for temperatures above the 65°

CxT - An interaction between the temperature and the balance point indicator, isWarm. CxT is the number of degrees this hour's measured temperature is above 65° F. The value is 0 for temperatures below the 65°

Lagged temperature-based inputs

The temperature-based inputs each have a corresponding time-lagged input. The time lagged variables are defined in the same method as the temperature-based variables but are calculated relative to the previous hours' temperature. The earliest time lagged input (for the earliest-reported time stamp for each pump) contains the same value as the non-lagged input.

Time based inputs

The time-based inputs are treated as categorical variables

- *Hour* – one of 24 values corresponding to the hour of the day
- *Month* – one of 12 values corresponding to the month of the year
- *Weekday* – one of 7 values corresponding to the day of the week
- *Weekend* – a binary indicator that the timestamp is occurring on a Saturday or Sunday
- *Daytime* – a binary indicator that the timestamp is occurring between 6am and 9pm (inclusive). Figure 4 shows mean flow rates for each hour of the day based on all collected data from all pump. This information was used to establish the "Daytime operating period" as 6 am to 9pm.

[33] The research team used this constant balance point in the model for all pumps. We acknowledge that it likely does not represent the balance point of all buildings or pump operation. However, it's purpose here as a model input is simply to associate the outside air temperature with typical heating or cooling. Therefore, to avoid further complicating the model, this single static temperature was used as opposed to specific balance points for each pump. Further, in many cases sufficient information was not available to determine the building specific balance point.

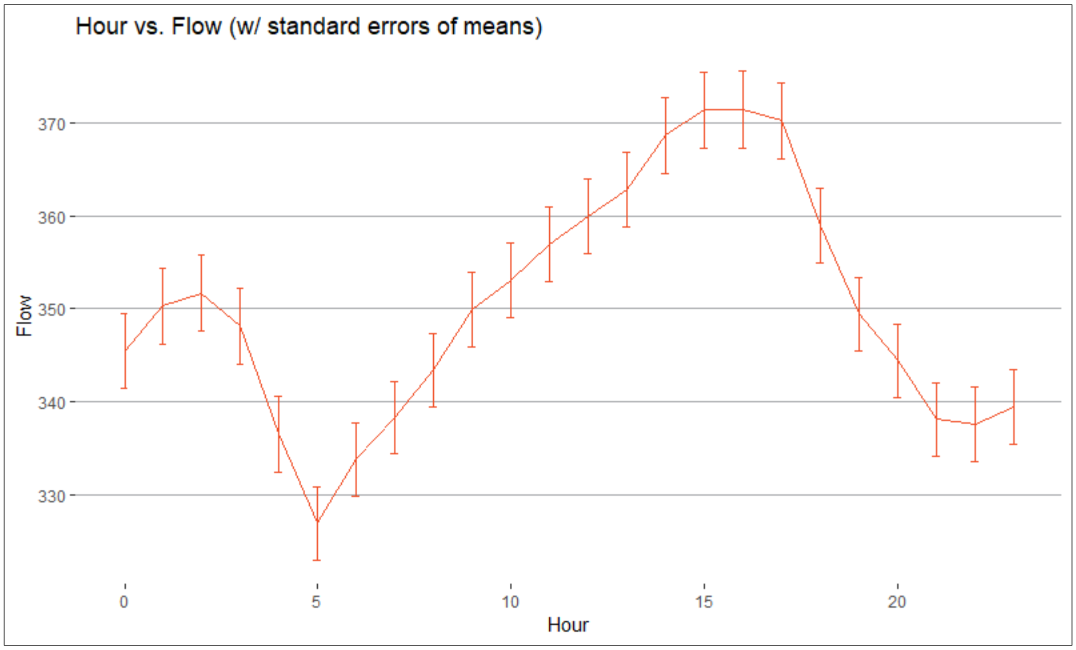

Figure 4: Hourly Flow Rates over the course of one day, for all pumps

The weekend and daytime variables allow the model to be more concise, but they will not provide additional explanatory power that isn't covered by the Weekday and Hour variables respectively.

4.2.4.3.3 Model Framework

The process estimates two generalized linear models for each pump reported. All inputs described above were possible inputs to both models for every pump in the research. It is known that not all the predictors will play a role in the final models (e.g., the weather input will not affect the prediction of the model for a non-weather dependent pump). Furthermore, all inputs are derived from relatively few variables, and it is expected that they have a large degree of collinearity. For these reasons the research team decided to perform a least absolute shrinkage and selection operator (LASSO) regression.

The calculations are conducted using the statistical programming language R. Specifically, the process uses a package[34] called *glmnet* to conduct the regressions. The *glmnet* package was specifically chosen because of its inclusion of regularization and advanced cross-validation methods.

LASSO regularization

Every regression involves finding the parameters that minimize a cost function (also known as an error function). The typical cost function is the sum of squared error (SSE). LASSO is one of several regularization techniques that add a component to the cost function to influence the behavior of the model. For a linear regression model, the LASSO regularization seeks to minimize the following cost function

[34] A package is a collection of functions and data sets that increase a programs functionality by applying pre-built tools

$$SSE + Regularization = \sum_{i=1}^{N} \left(y_i - \sum_{j=1}^{p} x_{ij}\beta_j \right)^2 + \lambda \sum_{j=1}^{p} |\beta_j| \qquad (10)$$

where

N	=	Number of Observations
p	=	Number of Parameters
y	=	True value (actual state or flow)
x	=	Value of model inputs (modeled state or flow)
β	=	Parameter being fit by the model
λ	=	Regularization rate
i	=	Point in time
j	=	Number of model inputs

The first component of this cost function is the same as one expects with a simple linear regression. The regularization component seeks to reduce the sum of the absolute value of the magnitudes of the coefficients. This tends to push unneeded variable coefficients to zero which allows LASSO to serve as a variable selection process. The process is also robust in eliminating multicollinear predictors for the final model.

The regularization component introduces the new parameter λ. The value for the λ parameter used is selected by fitting the model on multiple subsets of the data (see cross-fold validation below) on a series of values and selecting the one that yield the minimum estimated mean squared error.

Cross-validation
We validated that the model is not inappropriately over-fitting data sets by implementing a 10-fold cross validation process. This process involves randomly assigning the collection of data points considered into one of 10 subsets. The model is trained 10 times with each subset being held out in turn. Estimations are made for each of these subsets and error statistics are calculated. In this way, every data point is held-out for validation once and used to fit parameters 9 times. The distribution of errors across the 10 validation sets provides a strong estimate of the error for other data sets sampled from the population.

4.2.4.3.4 Model Form

All pumps included in the analysis have two models that create the annualized data set: (1) an operational model (state) and (2) conditional flow model (flow). Each of these models has distinctly different forms, which depend on the characteristics of the submitted pump operational data and any known operational characteristics of the pump available from the pump submitter.

Operational model (state)
When all known values of the operational state are the same, it is assumed to be a constant state pump and all annualized values are set to reflect that state.

When known operational procedure show that a pump has a known, repeated schedule, the data is extracted to include all data points up through the final whole week of collected data. That cycle is repeated to generate 8760 hours of operations.[35]

In all other cases, all we use all model inputs as predictors in a logistic regression with LASSO regularization. The LASSO regularization forced many parameters to 0 thereby selecting the variables most predictive of the operational hours

Conditional flow model (flow)
When all known values of the operational flow are the same, it is assumed to be a constant load pump and all annualized values are set to reflect that state.

In all other cases, the model uses all inputs as predictors in a linear regression with LASSO regularization. The LASSO regularization forced many parameters to 0 thereby selecting the variables most predictive of the operational hours

4.2.4.3.5 Stochastic Simulation

Model outputs for each time period serve as inputs into a stochastic simulation process that determines the estimated flows provided in the final annualized data set. This Section describes how the model outputs are used to generate the data.

The output of the operational model (logistic regression) is an estimated probability of the pump being on. An estimated state (on or off) is randomly selected according to the probability estimated by the model. The estimated state of the model is 0 if the pump is predicted to be off and 1 if the pump is estimated to be on. For pumps that should not be weather-dependent or have less than 2 weeks' worth of submitted data, state is estimated by repeating submitted values.

The output of the conditional flow model (linear regression) is a point estimate of the expected flow given that the pump is on. That point estimate is treated as a random variable following a Gaussian distribution centered on the estimate with a standard deviation equal to the standard deviation the flow values used in the training of the model. The Gaussian estimate was then multiplied by the frequency distribution of flow values in the model data set. This way, the model will only make predictions of flow values that were observed in the standardized data set. Also, the predictions will tend toward the original distribution of values. The result of the final step is normalized to represent a probability distribution from which a flow value is randomly selected as the final estimate of the flow.

4.2.4.3.6 Annualization with TMY3

To control the effect of weather on pump load, the research team used actual weather data for the period the pump was operating, as well as typical meteorological year weather data for a 30-year period (also known as normalized weather or TMY3 weather) from National Oceanic and Atmospheric Administration (NOAA) and National Solar Radiation Data Base, respectively.

The team mapped each pump location to a weather station based on the ZIP code associated with each pump. The closest weather station in the same climate zone to the pump was used as the representative

[35] The annualized data was annualized to 8,760 hours to eliminate the issues that would arise due to daylight savings time and leap years if annualized to the calendar year.

station. The team used actual weather in the training of the models then used a year (8,760 hours) of TMY3 data to adjust the pump load to reflect a typical meteorological year.

4.3 Results and Discussion

The research team analyzed the key variables, operating hours and Adjustment Factor, with the goal of answering the research questions presented in Section 4.1.2.

To analyze operating hours the research team initially looked at the operating hours of all pumps that fell within the three applications defined by the RTF UES Measures. The applications that the research collected pumps in are different than the applications established by the RTF. Shown in Table 28, the research applications are more granular than the RTF's applications. This relationship between RTF- and research-applications lent itself to analyzing the RTF applications first, then looking at operating hours on a more granular level.

Table 28: Crosswalk between RTF Measure Applications and Research Applications

RTF Measure Application	Research Application
Agricultural	Agricultural Irrigation
Commercial HVAC and DHW	Commercial Cooling Tower
	Commercial Cooling
	Commercial Heating
	Commercial Pressure Boost
Industrial and Municipal	Industrial, General
	Industrial, Cooling
	Industrial, BFW

First, Adjustment Factor was analyzed on a full-sample level, looking at all pumps collected for the research. The sample was then disaggregated by RTF Application and investigated on that level. The subfactors that affect Adjustment Factor (motor oversizing, BEP offset, load profile, and static head) were analyzed individually, then incorporated back into the high-level analysis of Adjustment Factor.

The research team also reviewed the available literature to corroborate or add to any findings available from the collection and analysis of new data as part of the research. However, the literature review revealed that the body of research that exists on commercial and industrial pumps almost never focuses on the efficiency or operation of the pump and was not applicable to the factors the research team was studying. Because pumps are most often ancillary equipment the research that addresses the efficiency of systems that Clean Water Pumps are installed on look at the efficiency of the equipment the pump serves (e.g., boilers, water heaters, chillers). If the research does address pumps, it is most often directed at correct design and installation of pumps for a system, not the operating characteristics of a pump after installation.

4.3.1 Operating Hours

The operating hours analysis looks at the average operating hours of each RTF Measure Application, and then disaggregates each application in an exploratory analysis with the goal of increasing the accuracy of the estimate and determining any dependencies in addition to the application.

The research team did not expect operating hours to depend on the speed control method; the need for flow within a given application should be independent from the method of pump control. This presumes that constant load pumps are either (1) controlled via throttling or bypass to provide the requisite amount of flow for the application or (2) providing too much flow to begin with in applications that are controlled based on time or some other system-independent variable. We tested this assumption throughout the analysis by comparing the operating hours within each application to the control case for each pump.

4.3.1.1 Agricultural Irrigation

Through investigation the analysis team determined that the sample collected supports the RTF's current estimate of 2,400 operating hours for agricultural irrigation and more granular disaggregation than at a sector level does not increase the accuracy of the operating hours estimates.

The agricultural (Ag) irrigation operating hours analysis includes a sample size of 143 pumps. The data collected for this sector is all existing data, with three main original-collection purposes: VSD Upgrades, Pump Tests, and RTF VFD Standard Protocol validation. Each original-collection purpose collected different data, and the calculation of operating hours is slightly different because of this.

VSD Upgrades; 21 pumps in the Ag sample are from VSD Upgrade Programs. VSD Upgrades are programs run by Utilities where an existing pump is retrofitted with a variable speed drive, allowing the speed to be reduced. This is a more energy-efficient method of reducing the flow through a pump than increasing the head. 21 pumps in the Ag sample are from VSD Upgrade Programs. These data submissions included monthly energy use (or monthly billing data) in kWh, the duration of each billing period in days (the billing period for the data submitted only spans the irrigation period), and the reported percent of the time the pump was off during the irrigation season. With this information operating hours is calculated as

$$OpHrs_{observed} = \left(\sum_{months} (Billing\ Period(days) * \frac{24hrs}{day} \right) * \left(1 - \%TimeOff_{pump}\right) \quad (11)$$

where

$OpHrs_{observed}$ = Observed Operating Hours (hrs)
$Billing\ Period$ = Number of Days in the billing period (days)
$\%TimeOff_{pump}$ = Percent of time the pump was not operating (%)

The original purpose of this data was to determine energy savings from changing from constant speed control to variable speed control, so this data set includes information for each pump when operating both as a variable speed pump and as a constant speed pump.

Pump Tests; 45 pumps included in the analysis are from Pump Tests. Pump Tests are. These data submissions include the annual energy usage in kWh and the power input to the pump system in kW. The operating hours calculation for this data source is

$$OpHrs_{observed} = \frac{AnnualEnergyUsage(kWh)}{PowerInput(kW)} \quad (12)$$

where

$OpHrs_{observed}$	=	Observed Operating Hours (hrs)
$AnnualEnergyUsage$	=	Annual energy consumption (kWh)
$PowerInput$	=	Measured power input to the pumping system (kW)

This calculation is only used for constant speed pumps. The same calculation method for variable speed pump requires information on the power input to the pumping system at various load points, as well as the percent of time the pump spends at those load points. The data submissions do not include this information, so operating hours for variable speed pumps submitted from this data source were not calculated.

RTF VFD Standard Protocol Information; The RTF used this data originally in an analysis for the Standard Protocol developed for the addition of a VFD to an irrigation pump. 77 Ag pumps are from this data source. These submissions include the reported annual operating hours and the calculated annual operating hours, where Equation 13 represents the method used for determining calculated annual operating hours.

$$OpHrs_{calculated} = \frac{AnnualEnergyUsage(kWh)}{MotorHP * 0.746} \quad (13)$$

where

$OpHrs_{calculated}$	=	Calculated Operating Hours (hrs)
$AnnualEnergyUsage$	=	Annual energy consumption (kWh)
$MotorHP$	=	Horsepower of the Motor attached to the pump

In the analysis performed to support the previous standard protocol, they (the previous analysts) used the lesser of the two operating hours values (between reported and calculated). The analysis team for this report decided to use the reported operating hours, citing two main reasons:

1) The report summarizing the previous analysis performed using these data indicates that the average energy consumption that is in the data set may include significant loads that are not the pump. The review of that analysis called into question the dependability of the energy consumption values, and this introduced uncertainty into the results that the team reviewing the analysis were not comfortable with.
2) The equation for calculated operating hours does not account for any motor oversizing and assumes the motor operates at the rated horsepower. Motor oversizing is a variable included in the development of Adjustment Factor and is a factor this research investigates.

The research team calculated the average operating hours for all the agricultural pumps collected and determined the related statistics. Table 29 shows the statistical analysis of the average application operating hours, compared to the data used for the RTF OpHrs Estimate. As the table shows, the average operating hours observed in this study and the original RTF OpHrs estimate are within the 90% Confidence Interval of each other. When rounded to the hundreds, which is the place to which the RTF rounded, the values are the same (2,400 hours).

Table 29: Average Agricultural Pump Operating Hours and Statistical Analysis, observed and RTF Estimate

Statistic	All Pumps, Observed	RTF OpHrs Estimate
No. of Pumps in the sample (n)	139	280
Average	2,358	2,386
Max	6,709	7,745
Min	240	814
Standard Deviation	1,120	1,225
Standard Error	95	73
90% Margin of Error	157	121
90% Confidence Interval	2,201 to 2514	2,265 to 2507

The estimate developed for the RTF UES measures is based on two data sets: (1) Operating hours from the Green Motor Rewind Program[36] and (2) Operating hours information from BPA's Ag Irrigation program[37]. The RTF's second data source includes information from BPA's Ag irrigation program, which was a data source for this research. To avoid including the same data in both the observed data set and the RTF OpHrs Data set the team removed those pumps from the 280 pumps calculating the RTF OpHrs calculated average and statistical analysis in Table 29. The sample size for this analysis and the original RTF analysis is different because along with the 77 pumps from the BPA data set, the RTF also used 280 pumps from the Green Motor Rewind Program. To test the impact the BPA data has on the operating hours estimate (and ensure that inclusion of this data in both averages is not skewing the results) the analysis calculated the observed average without the BPA data. Table 30 shows that the average operating hours increases to 2,412 when the 77 BPA pumps are removed, which is closer to the estimate from the RTF shown in Table 29. When these operating hours values are taken together, the analysis team concludes, with a high degree of confidence, that the average operating hours for agricultural pumps is 2,400.

Table 30: Average Observed Agricultural Pump Operating Hours and Statistical Analysis, without BPA Data

Statistic	All Pumps, Observed
No. of Pumps in the sample (n)	62
Average	2,412
Max	6,709
Min	240
Standard Deviation	1,333
Standard Error	169
90% Margin of Error	279
90% Confidence Interval	2,133 to 2,691

[36] The data from the Green Motor Rewind can be found on the "Ag Irrig hours" tab of ComIndAgPumps_1_1.xlsm on the RTF Website
[37] The data from BPA's Ag Irrigation Program can be found on the "SavingsData" tab of AgPumpVFD_analysis_v1.xlsm on the RTF Website

In addition to average operating hours for all pumps in the agricultural sector, the research team investigated whether the operating hours in this sector varied significantly based on other characteristics of the pumps, including the speed control method and motor HP. When looking at the data for constant speed versus variable speed pumps, the average operating hours were not statistically different from each other or the mean for all pumps (for constant speed pumps the average is 2,281 hours (n=52 pumps) and for variable speed pumps the average operating hours is 2,404 hours (n=87 pumps)).

The analysis also looked at the operating hours disaggregated by motor HP to determine if a correlation exists between the size of the pump system and the operating hours in this sector. Figure 5 shows the average operating hours for each motor HP submitted (blue dots), with error bars set to display the 90% confidence interval for each motor HP. Figure 5 also displays the observed OpHrs estimate (orange dashed line). As is evident from the graph, there does not appear to be a significant trend in operating hours with respect to motor HP.[38] However, there is more scatter in operating hours for lower horsepower pumps, likely because the sample size for these motor HP's is lower than the sample size for the larger motor HP's. Table 31 shows that when grouped into three bins of approximately the same sample size the average operating hours are within the 90% confidence interval of the sector average.

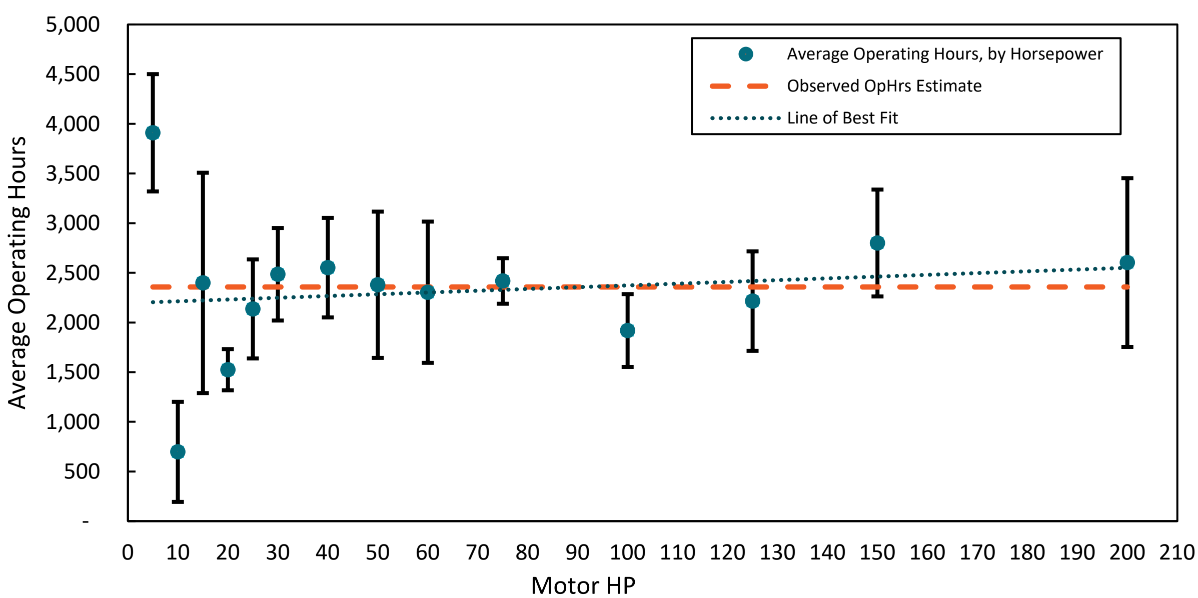

Figure 5: Agricultural Operating Hours, by Motor HP

[38] The p-value calculated for this data is 0.61, showing the event is not statistically significant (if p-value is less than 0.05 the event is statistically significant. If the p-value is greater than 0.05 the event is not statistically signifant).

Table 31: Agricultural Pumps, Average Operating Hours by Motor HP Range, Statistical Analysis

Motor HP Range	n	Average (hrs)	Max (hrs)	Min (hrs)	Standard Deviation	Standard Error	90% Margin of Error
0 < Motor HP ≥ 30	43	2,252	4,859	240	1,214	185	306
30 < Motor HP ≥ 75	52	2,346	6,709	324	1,054	146	241
75< Motor HP ≥ 200	44	2,358	5,040	845	1,119	169	278

While establishing the bins decreased the variability seen in the average operating hours by motor HP, the motor HP Bin average operating hours are less precise than the application-wide operating hours, as described by the standard errors (the standard error for all three motor HP Bins are larger than the application-wide operating hours standard error).

Based on this analysis, the research team concludes that the average operating hours for the agricultural sector are approximately 2,400 and do not vary significantly based on pump speed control method or motor HP.

4.3.1.2 Commercial HVAC and DHW

The research team collected data on 161 Commercial HVAC and DHW pumps that included sufficient information to analyze operating hours[39]. As shown in Table 28, the research applications included under this RTF Application include Commercial Cooling, Commercial Cooling Tower, Commercial Heating, and Commercial Pressure Boost[40]. The team first performed a high-level analysis of the operating hours and compared the results to the estimate from the RTF analysis. The three sources the RTF used to develop their estimate (refer to Section 4.1.2 for more information on these sources) are not available for a statistical analysis and comparison to the observed average operating hours. The statistical analysis of the observed pumps in Table 32 shows that the observed average operating hours for Commercial HVAC and DHW pumps is 3,753. If rounded to the nearest thousands it would be the same value as the RTF estimate (4,000). Table 32 also shows that there is a significant amount of variability in the observed operating hours. To investigate the source of this variation and determine if any of the variation could be explained by additional variables, the team disaggregated the data based on motor HP, speed control method, and research application.

---

[39] There were samples submitted that did not include logged operational data, which made it impossible to estimate operating hours. The inverse is also true for adjustment factor; some pumps were submitted with operational data, but not enough audit data to determine the pump type or nominal speed.

[40] As discussed in Section 4.2.3 the research team dropped Commercial DHW Recirculation from the Clean Water Pumps sample strata because it is almost exclusively served by Circulators.

Table 32: Average Operating Hours and Statistical Analysis, Commercial HVAC and DHW

Statistic	All Pumps, Observed
No. of Pumps in the sample	161
Average	3,753
Max	8,760
Min	-
Standard Deviation	2,889
Standard Error	228
90% Margin of Error	376
90% Confidence Interval	3,377 to 4,129

The team observed no obvious or notable correlation between motor HP and operating hours when analyzing the operating hours for this application based on motor HP.[41] Figure 6 shows the average operating hours for each motor HP (blue dot), with error bars for each average representing the 90% Confidence Interval. The orange line represents the application-level average, and the dotted lines represent the upper and lower bounds of the application-level 90% confidence interval. Visually the line of best fit increases slightly across the range of motor HPs. The slope of the line of best fit is 1.8077; this means the range of operating hours it would predict across the range of HPs considered by the RTF measures (1 to 200 HP) would be 3,930 to 4,292.

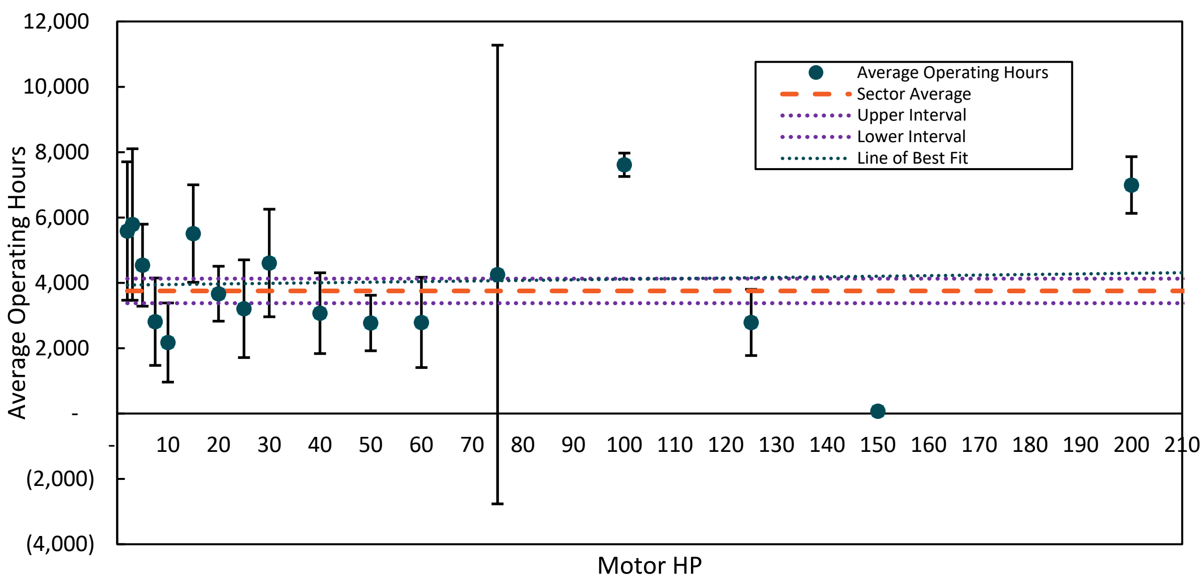

Figure 6: Average Commercial HVAC and DHW Operating Hours, by Motor HP

[41] With a p-value of 0.20 the research team determined the event not statistically significant.

The team also reviewed the statistics for these average operating hour values. For almost all the motor HP bins (all but 2 motor HP's), the motor HP bins have a larger standard error than the standard error for the application-level average, which indicates that disaggregating by motor HP did not increase the accuracy of the average operating hours, as presented in Table 33.

Table 33: Average Commercial HVAC and DHW Operating Hours, Statistical Analysis by motor HP

Motor HP	n	Average (hrs)	Max (hrs)	Min (hrs)	Standard Deviation	Standard Error	90% Margin of Error
2	8	5,586	8,760	205	3,632	1,284	2,119
3	3	5,785	8,596	4,380	2,434	1,405	2,319
5	11	4,541	8,760	-	2,523	761	1,255
7.5	16	2,811	8,760	-	3,243	811	1,338
10	12	2,173	8,760	-	2,543	734	1,211
15	14	5,509	8,760	-	3,383	904	1,492
20	14	3,668	7,101	-	1,906	509	841
25	8	3,209	8,589	60	2,563	906	1,495
30	6	4,608	8,218	643	2,443	998	1,646
40	15	3,072	8,760	-	2,902	749	1,236
50	20	2,771	8,513	-	2,303	515	850
60	9	2,789	8,760	-	2,512	837	1,382
75	2	4,255	8,509	-	6,017	4,255	7,020
100	6	7,613	8,313	6,684	532	217	358
125	6	2,788	4,574	-	1,503	614	1,013
150	3	74	82	82	8	4	7
200	2	6,995	7,520	6,469	743	526	867
250	6	4,613	5,887	2,557	1,522	621	1,025

The team also evaluated the relationship between operating hours and motor HP for larger groupings of motor HP to confirm that the small sample size in each motor HP was not driving the standard error up and overpowering an underlying trend in the data. In order to test this the pumps were grouped into four motor HP bins with approximately the same sample size and the same statistical analysis was performed.

Table 34 shows that the average operating hours for all six motor HP bins fall within the 90% confidence interval of the RTF Application-level average. The standard error for each of these averages is larger than the RTF-level average, showing that the disaggregation isn't increasing the accuracy of the average.

Table 34: Average Commercial HVAC and DHW Operating Hours, Statistical Analysis by motor HP Bin

Motor HP Range	n	Average (hrs)	Max (hrs)	Min (hrs)	Standard Deviation	Standard Error	90% Margin of Error
0< Motor HP ≥5	22	5,091	8,760	-	2,883	615	1,014
5 < Motor HP ≥ 10	28	2,538	8,760	-	2,930	554	913
10 < Motor HP ≥ 20	28	4,588	8,760	-	2,853	539	890
20< Motor HP ≥40	29	3,427	8,760	-	2,702	502	828
40< Motor HP ≥60	29	2,776	8,760	-	2,324	432	712
60 < Motor HP ≥250	25	4,512	8,509	-	2,512	502	829

We also reviewed the operating hours by speed control method. As Table 35 shows, the average operating hours for constant speed Commercial HVAC and DHW pumps are much higher than the average operating hours for variable speed Commercial HVAC and DHW pumps.

Table 35: Average Commercial HVAC and DHW Operating Hours, Statistical Analysis by Speed Control Method

Speed Control Method	n	Average (hrs)	Max (hrs)	Min (hrs)	Standard Deviation	Standard Error	90% Margin of Error
Constant Speed	27	6,074	8,760	5	2,834	545	900
Variable Speed	134	3,285	8,760	-	2,675	231	381

However, as Figure 7 shows, both constant speed and variable speed pumps demonstrate a wide range of observed operating hours, from <1000 hours to 24/7 operation (8760 hrs). Figure 7 shows the pump operating hours, with Commercial Cooling, Heating, and Cooling Tower represented by the green and red dots (for constant and variable speed, respectively) and Pressure Boost represented by the blue and purple dots (for constant and variable speed, respectively). This representation breaks apart the 'HVAC' and 'DHW' portions of the RTF Application "Commercial HVAC and DHW".

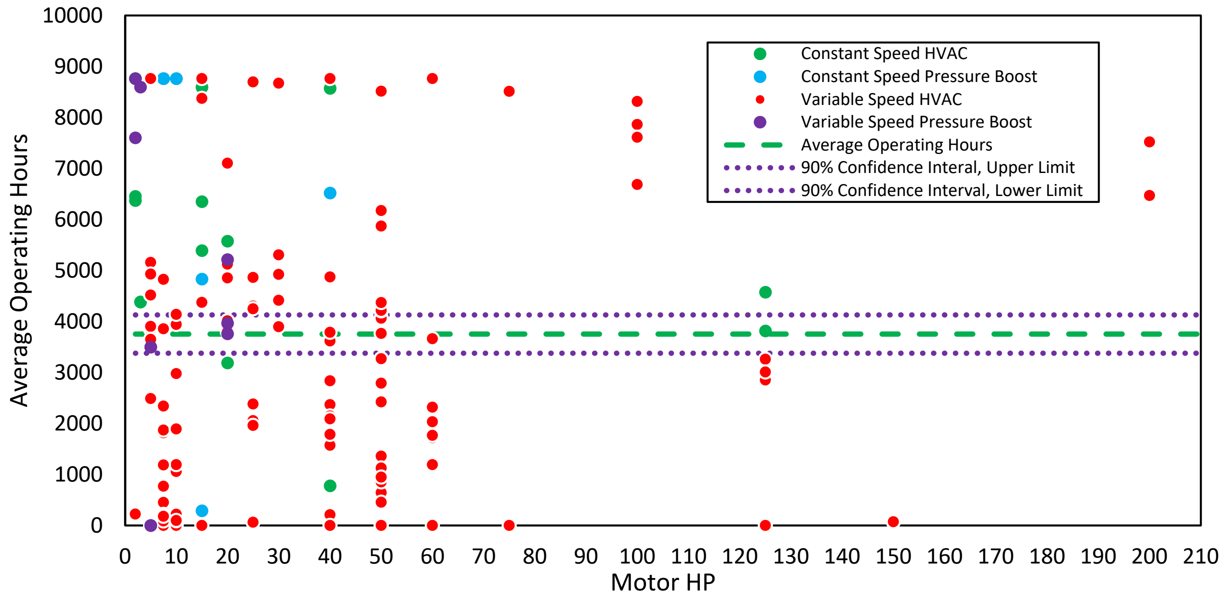

Figure 7: 'Commercial HVAC and DHW' Operating Hours, by motor HP

Figure 7 does not seem to demonstrate a significant relationship between the speed control method and operating hours. This figure shows a large amount of variability in the all applications and speed control methods. Without a distinct patter presenting itself the research team evaluated the average operating hours by research application. When the average operating hours are presented disaggregated by application, as they are in Table 36, it becomes evident that the operating hours in the Pressure Boost research application is drastically higher than in the Cooling, Cooling Tower, and Heating research applications. The difference in operating hours between Cooling and Cooling Tower is not statistically significant, while the Heating operating hours is approximately 2000 hours larger than Cooling and Cooling Tower.

Table 36: Average Commercial Sector Operating Hours, Statistical Analysis by Application

Application	Cooling	Cooling Tower	Heating	Pressure Boost
No. of Pumps in the sample	75	39	26	21
Average	2,978	3,211	4,964	6,028
Max	8,760	8,503	8,760	8,760
Min	-	-	-	-
Standard Deviation	2,327	2,708	3,137	3,213
Standard Error	269	434	615	701
90% Margin of Error	443	716	1,015	1,157
90% Confidence Interval	2,534 to 3,421	2,495 to 3,927	3,949 to 5,979	4,872 to 7,185

The research team attempted to confirm that the research application (DHW Pressure Boost versus commercial HVAC pumps) was the key variable driving the previously observed difference in operating hours between speed control cases by evaluating the average operating hours for the two speed control cases with pressure boost pumps removed. These results are show in Table 37, which shows that constant speed and variable speed still maintain meaningful differences, even with the Pressure Boost research application removed.

Table 37: Average Commercial HVAC and DHW Operating Hours, Statistical Analysis by speed Control Method with Pressure Boost removed

Speed Control Method	Constant Speed	Variable Speed
No. of Pumps in the sample	16	124
Average	5,143	3,188
Max	8,760	8,760
Min	5	-
Standard Deviation	2,607	2,625
Standard Error	652	236
90% Margin of Error	1,075	389
90% Confidence Interval	4,068 to 6,218	2,799 to 3,577

By disaggregating the pumps even further, into speed control and application averages, as in Table 38, the team saw that the applications with small sample sizes (Constant Speed Cooling and Cooling Tower) has a large difference between the speed control operating hours, whereas Heating, which had an n ≥ 10 for both speed control methods, had much closer operating hours. The research team feels that the low sample size in Constant speed HVAC Pumps is a factor in driving the difference in operating hours.

Table 38: Commercial HVAC pumps Operating Hours, Statistical Analysis by Application and Speed Control Method

Application	Speed Control	n	Average	Max	Min	Std Deviation	Std Error	90% Margin of Error	90% Confidence Interval
Cooling	Constant Speed	4	5,125	6,348	4,380	2,147	1,074	1,771	3353 to 6896
	Variable Speed	71	2,857	8,760	-	944	112	185	2672 to 3042
Cooling Tower	Constant Speed	2	4,707	8,503	910	5,369	3,797	6,264	-1558 to 10971
	Variable Speed	37	3,130	8,313	-	2,610	429	708	2422 to 3838
Heating	Constant Speed	10	5,238	8,760	5	2,359	746	1,231	4007 to 6469
	Variable Speed	16	4,793	8,760	-	3,269	817	1,348	3445 to 6141

Table 38 shows that the only application where the speed control average operating hours fall within the other speed control case's confidence interval. The variation in the samples for the other two applications could be a function of the small sample size.

4.3.1.3 Industrial and Municipal

In the original RTF Measures, the Industrial and Municipal Sectors are estimated to operate the same amount of time, 5000 hrs/yr. This estimate was developed based on data in the Northwest Motor Database (NW Motor Database).[42] The average observed in the pumps collected in this research is 5,242 hours per year, which is consistent with the original RTF analysis and the information from the NW Motor Database has a much larger number of pumps included in the sample, as shown in Table 39. One of the goals of the research was to validate the operating hours estimate made by the RTF, and the research team felt that incorporating the NW Motor Database pumps (similarly to how the BPA Agricultural pump data was incorporated) would not be beneficial because the size of that data set is two orders of magnitude larger than all other industrial pumps included in the research and would make up 97% of the sample.

Table 39: Industrial and Municipal Operating Hours, Statistical Analysis

Statistic	All Pumps, Observed	NW Motor DB
No. of Pumps in the sample	105	2,911
Average	5,242	5,886
Max	8,760	8,760
Min	-	1
Standard Deviation	3,388	2,694
Standard Error	331	50
90% Margin of Error	546	82
90% Confidence Interval	4,696 to 5,787	5,804 to 5,968

The operating hours, disaggregated by sector, show a few distinct patterns. Figure 8 shows the operating hours of all pumps in the sample vs motor HP and colored based on sector. In this figure it is evident that the industrial pumps sampled for this research, in general, have smaller size motors than Municipal pumps and more frequently operate 8,760 hours per year. This is not surprising when thinking critically about the applications of pumps in each sector. Municipal pumps are most times, even in small municipalities, serving large systems and large loads. This suggests that the operating hours may vary significantly by Application. Table 40 shows the operating hours averaged by sector, which demonstrates that the average Industrial operating hours, 6,175, is almost double the Municipal operating hours of 3,360 hours.

[42] More information on the NW Motor Database can be found in Section 4.2.1 of this report, and online at https://rtf.nwcouncil.org/subcommittee/northwest-industrial-motor-database-summary

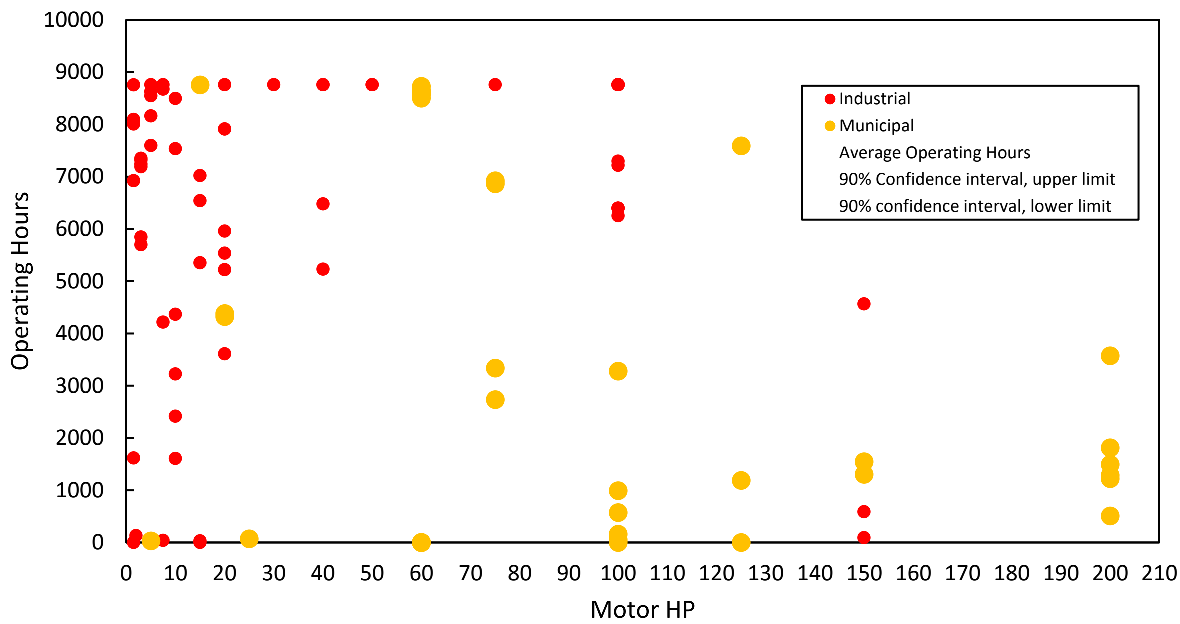

Figure 8: Industrial and Municipal Operating Hours, Average by Sector

Table 40: Industrial and Municipal Operating Hours, Average by Sector

Statistic	All Pumps, Observed	Industrial	Municipal
No. of Pumps in the sample	105	69	37
Average	5,242	6,175	3,360
Max	8,760	8,760	8,756
Min	-	-	-
Standard Deviation	3,388	2,978	3,444
Standard Error	331	359	566
90% Margin of Error	546	592	934
90% Confidence Interval	4,696 to 5,787	5,584 to 6,767	2,425 to 4,294

As described in Section 4.2.3, during data collection the research team broke the Industrial Sector into two unique Industrial applications: Industrial Cooling and Industrial Boiler Feedwater (with Industrial General as a category to incorporate pumps collected outside these two categories). When the Industrial sector is disaggregated by application (as they are in Table 41), the average operating hours between Industrial Cooling and Industrial BFW are significantly different, with Industrial Cooling operating 6,828 hours, more than 2000 more than the Industrial BFW operating hours of 4,119.

Table 41: Industrial Observed Operating Hours, by Application

Statistic	Industrial All	Industrial Cooling	Industrial BFW Pump	Industrial General
No. of Pumps in the sample	69	41	13	14
Average	6,175	6,828	4,119	6,614
Max	8,760	8,760	8,760	8,760
Min	-	-	-	-
Standard Deviation	2,978	2,483	3,597	2,603
Standard Error	359	388	998	696
90% Margin of Error	592	640	1,646	1,148
90% Confidence Interval	5,584 to 6,767	6,188 to 7,468	2,473 to 5,765	5,466 to 7,762

Based on this analysis the research team believes that the operating hours of the Industrial sector and Municipal sector are significantly different from each other. The team also sees a significant difference between the Industrial Sub-applications, supporting the decision to disaggregate the application.

4.3.2 Adjustment Factor

Adjustment Factor is the second key variable that impacts the consumption and savings from pumps based on the RTF energy savings equation shown in Section 4.1.1. The Adjustment Factor exists to account for differences between actual system energy consumption and the energy consumption predicted by the RTF simplified energy equation, which assumes a certain load profile (in the PEI rating) and pump/motor sizing, as described in Section 4.1.1. The team analyzed Adjustment Factor in stages because of the impact multiple variables have on the value. First, the research team calculated the Adjustment Factor for each pump directly and analyzed the high-level characteristics of that calculated Adjustment Factor. This analysis is presented in Section 4.3.2.1. Then, the research team evaluated the Adjustment Factor based on specific "sub factors" - including motor oversizing, static head, load profile, and BEP offset - to better understand the pump system and installation characteristics driving the variability in Adjustment Factor. This analysis is presented in Sections 4.3.2.2.1 through 4.3.2.2.4. Finally, based on the sub-factor analysis, the team presents a final review of the overall Adjustment Factor in section 4.3.2.3. Note that sub-factor analysis on agricultural pumps was not possible due to lack of granularity in the submitted data.

4.3.2.1 High-Level Adjustment Factor

The first analysis of Adjustment Factor looks at the observed Adjustment Factor for all pumps, calculated as the annual pump energy consumption determined based on the submitted data divided by the calculated pump energy consumption calculated based on the RTF simplified methodology, as shown in Equation 14:

$$AdjFactor_{Obs} = \frac{PumpSystemEnergyConsumption_{actual}}{MotorHP * 0.746 * OpHrs_{Obs} * PEI} \quad (14)$$

where

$$AdjFactor_{Obs} = \text{Observed Adjustment Factor}$$
$$PumpSystemEnergyConsumption_{actual} = \text{Observed Annual Energy Consumption (kWh)}$$
$$MotorHP = \text{Motor HP}$$
$$OpHrs_{Obs} = \text{Observed Annual Operating Hours}$$
$$PEI = \text{Pump Energy Index}$$

To calculate the energy consumption based on the RTF simplified methodology, the specific motor HP, operating hours, and PEI for that pump are considered. For pumps without a PEI, the PEI is determined based on the submitted pump model information, as discussed in Section 4.2.1.

Table 42 shows the average observed Adjustment Factor for all pumps that are operating, along with the statistical analysis. This analysis does not include the pumps that have zero operating hours; the energy consumption model accounts for pumps that do not operate in the operating hours term. The maximum Adjustment Factor is 2.799, which represents a variable speed pump that operates at or near max operation for the entire time the pump is operating (which is very different than the load profile assumed by the PEI rating).

Table 42: Observed Adjustment Factor, Statistical Analysis

Statistic	All Pumps, Observed
No. of Pumps in the sample	210
Average	0.852
Min	0.015
Max	2.799
Standard Deviation	0.511
Standard Error	0.035
90% Margin of Error	0.058
90% Confidence Interval	0.794 to 0.910

A histogram of all calculated Adjustment Factors, in Figure 9, shows a concentration of Adjustment Factor between 0.4 and 1.2. The concentration of Adjustment Factors is weighted towards the lower end of the distribution. The research team looked at each Adjustment Factor as a function of other parameters of the research to see if there were any trends that could further explain the range of Adjustment Factors observed in the data.

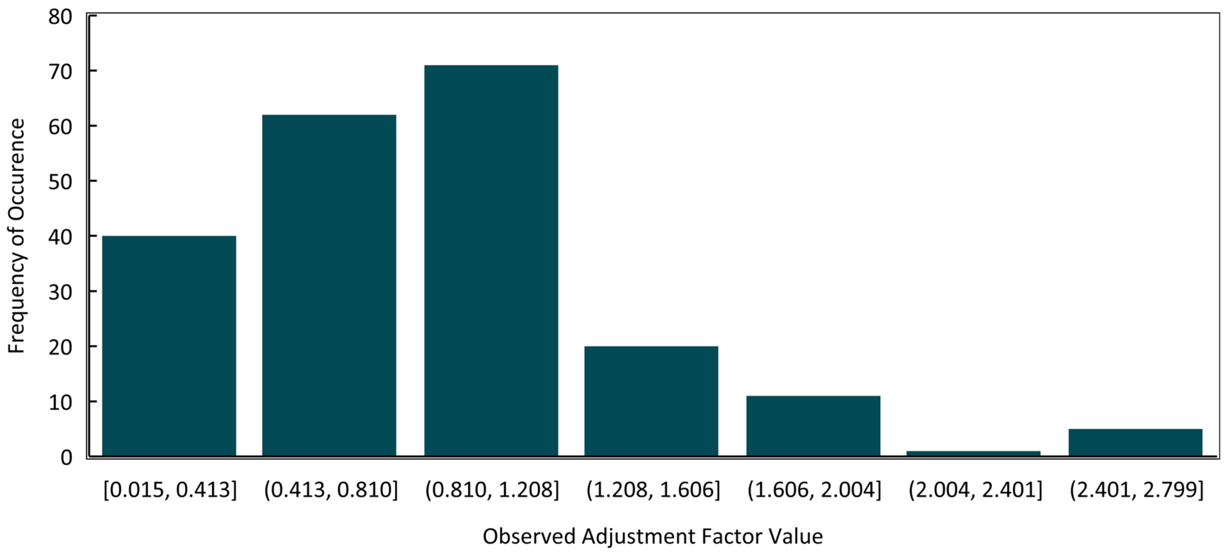

Figure 9: Histogram of Adjustment Factor, All Pumps

Figure 10, Figure 11, and Figure 12 show the observed Adjustment Factor vs operating hours, motor HP, and PEI, respectively.

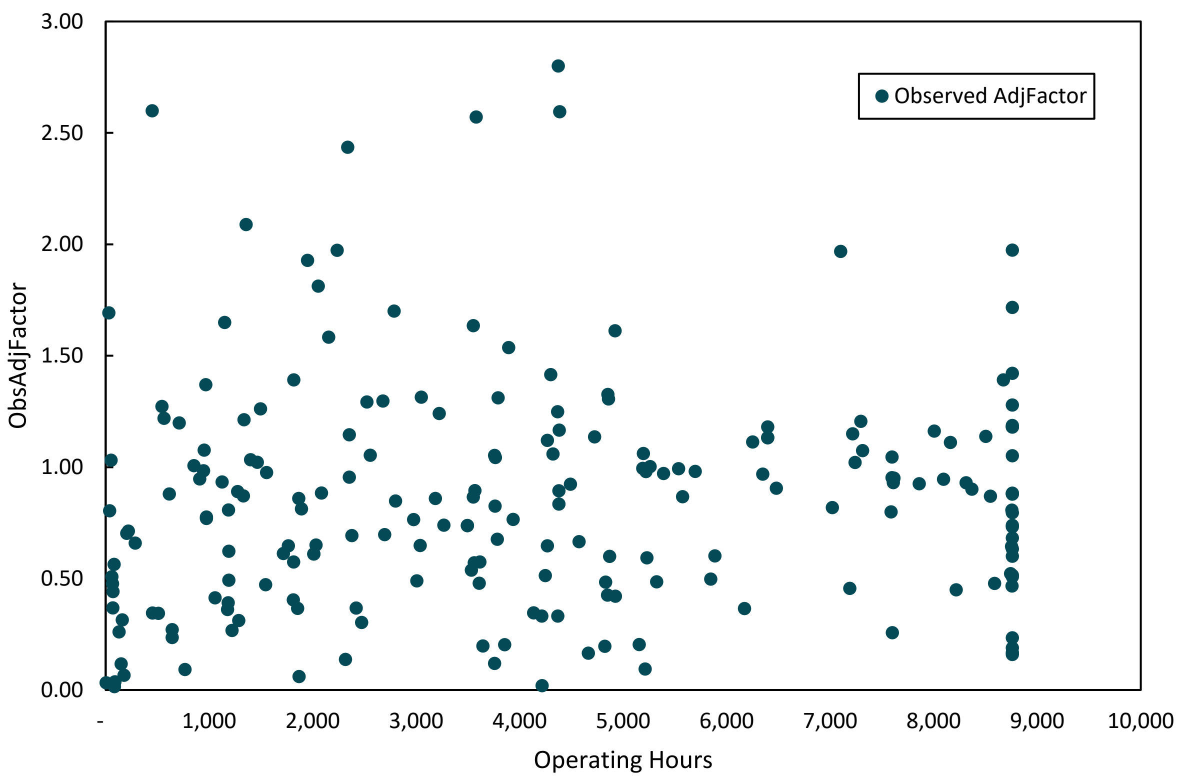

Figure 10: Observed Adjustment Factor vs Operating Hours

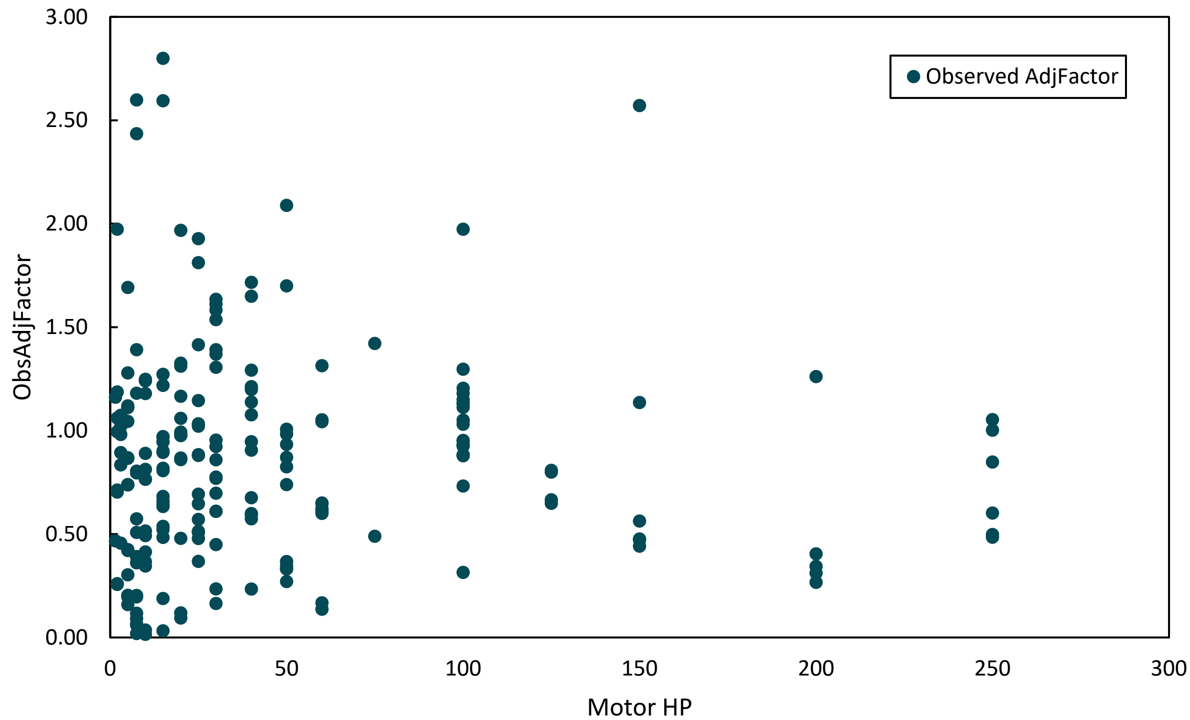

Figure 11: Observed Adjustment Factor vs Motor HP

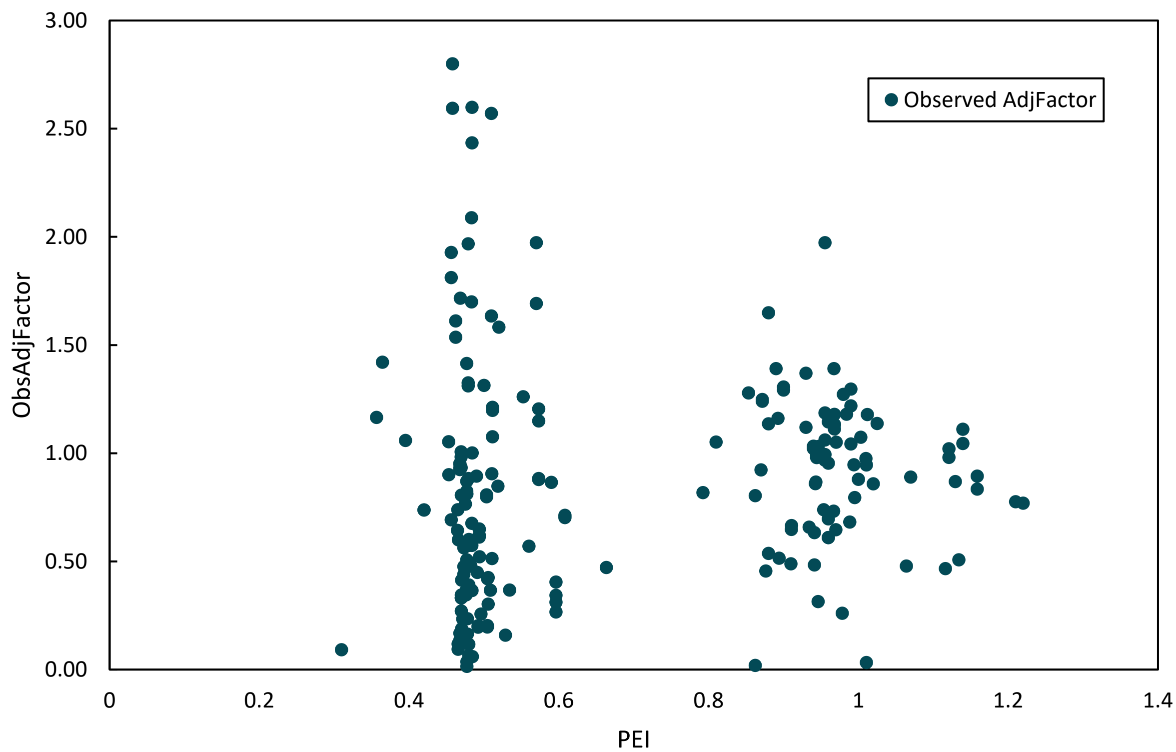

Figure 12: Observed Adjustment Factor vs PEI

There is no obvious pattern present in Figure 10 There is a concentration of pumps at 8,760 hours, but that is not unexpected as it is the highest operating hour value that is possible. Figure 11 has what looks like a clustering of pumps below 100 motor HP, but this is due to the majority of the pumps collected for the research falling into that size range. Figure 12 has two clusters of pumps, one between PEI of 0.45 and 0.6, which is typical of variable speed pumps, and one between 0.8 and 1.2, which is typical of constant speed pumps. These clusters are not surprising, but the difference in the range of Adjustment Factor values for each group stood out, which led the research team to start the analysis of Adjustment Factor by disaggregating by speed control method. As shown in Table 43, the average for constant vs. variable speed pump was similar, but the range of Adjustment Factors is much more variable for the variable speed pumps.

Table 43: Adjustment Factor Statistical Analysis, by Speed Control Method

Speed Control Adjustment Factor	Constant Speed Adjustment Factor	Variable Speed Adjustment Factor
No of Pumps in Sample	83	127
Average	0.924	0.805
Min	0.019	0.015
Max	1.973	2.799
Standard Deviation	0.328	0.598
Standard Error	0.036	0.053
90% Margin of Error	0.059	0.088
90% Confidence Interval	0.864 to 0.983	0.717 to 0.893

Figure 13 and Figure 14 show the distributions of Adjustment Factor for constant speed pumps and variable speed pumps, respectively. The there is a much tighter, normal distribution of Adjustment Factors for constant speed pumps. The variable speed pump Adjustment Factor spans a range twice as large as constant speed, with a concentration below 1.21. This concentration around and below 1.00 is due to the fact that one of the factors that impacts Adjustment Factor is load profile and variable speed pumps are designed to be able to efficiently operate at lower flow rates.

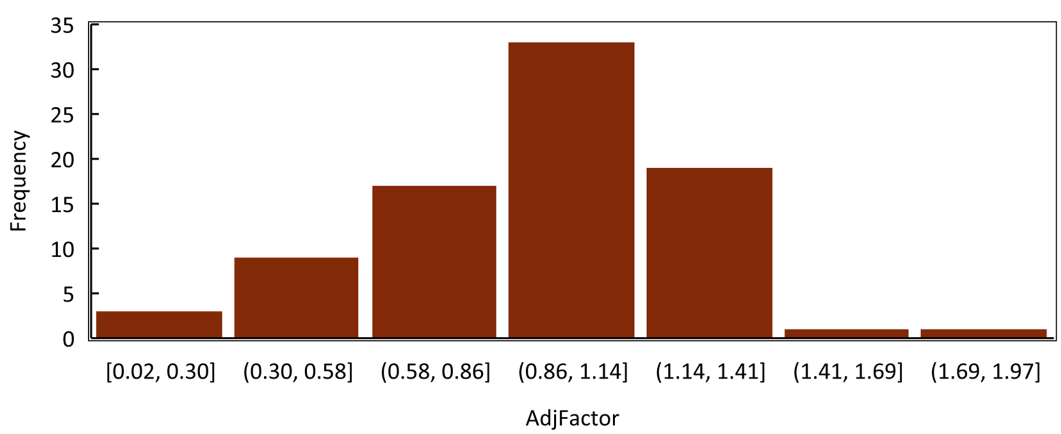

Figure 13: Histogram of Adjustment Factor, Constant Speed Pumps

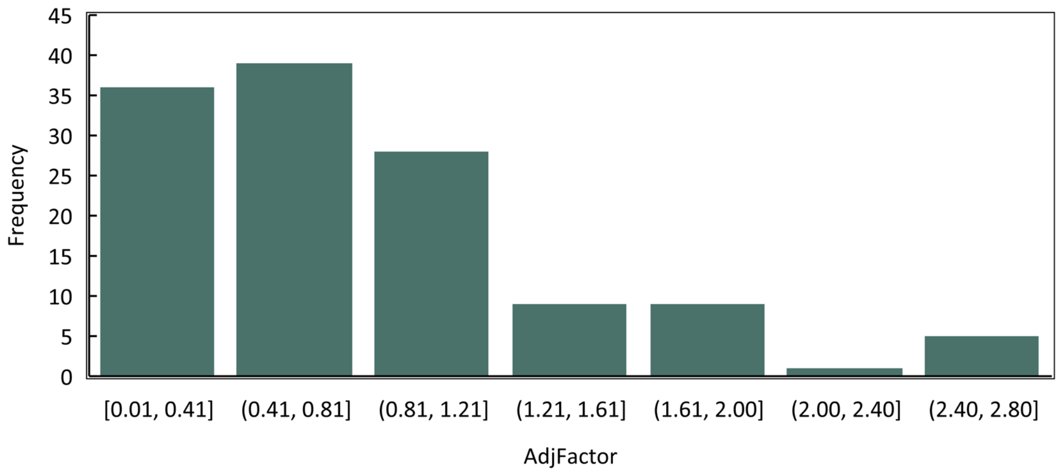

Figure 14: Histogram of Adjustment Factor, Variable Speed Pumps

The Observed Adjustment Factor, when disaggregated by Pump Class and by speed control method is shown in Table 44. Table 45 includes the Adjustment Factors used by the RTF Measures. The Adjustment Factors are, in general, higher for ST pumps than other pump types, for both constant and variable speed pumps. The RTF also established its Adjustment Factors for ST pumps higher than the other pumps due to anecdotal evidence that different sizing methods that are used for ST pumps, resulting in a different motor oversizing factor and therefore different Adjustment Factor for those pumps. The research team also investigated the IL, 3600 Pumps because they are higher than all other pumps (apart from ST) and determined that small sample sizes at this level of disaggregation were likely causing bias in the calculated Adjustment Factor for some pump speed/class combinations. For example, for IL, 3600, Constant Speed there were only 2 pumps in this class, and both are from the same system. For Variable Speed there were only 3 pumps in this class and all three are from the same system.

Table 44: Average Observed Adjustment Factor, by Pump Class and Nominal Speed

Speed Control	Pump Class	Nominal Speed	n	Average	Max	Min	Std Dev	Standard Error	90% Margin of Error	90% Confidence Interval
CS	**ESCC**	**1,800**	**24**	0.979	1.973	0.032	0.339	0.069	0.114	0.865 to 1.093
CS	**ESCC**	**3,600**	**8**	0.830	1.272	0.456	0.325	0.115	0.189	0.64 to 1.019
CS	**ESFM**	**1,800**	**5**	0.893	1.179	0.648	0.230	0.103	0.170	0.723 to 1.062
CS	**ESFM**	**3,600**	**5**	0.847	1.137	0.658	0.197	0.088	0.145	0.702 to 0.992
CS	**IL**	**1,800**	**15**	0.772	1.278	0.260	0.282	0.073	0.120	0.651 to 0.892
CS	**IL**	**3,600**	**2**	1.244	1.248	1.240	0.006	0.004	0.006	1.238 to 1.251
CS	**ST**	**3,600**	**8**	1.183	1.649	0.489	0.357	0.126	0.208	0.975 to 1.391
CS	**RSV**	**1,800**	**8**	0.960	1.180	0.314	0.296	0.105	0.173	0.788 to 1.133
CS	**RSV**	**3,600**	**5**	0.695	1.296	0.019	0.467	0.209	0.344	0.35 to 1.039
CS	**ST**	**1,800**	**3**	1.054	1.136	0.975	0.080	0.046	0.076	0.978 to 1.131
VS	**ESCC**	**1,800**	**3**	0.609	0.901	0.449	0.253	0.146	0.241	0.368 to 0.85
VS	**ESCC**	**3,600**	**6**	0.470	0.865	0.094	0.333	0.136	0.224	0.246 to 0.695
VS	**ESFM**	**1,800**	**17**	0.813	1.967	0.136	0.590	0.143	0.236	0.577 to 1.049
VS	**ESFM**	**3,600**	**4**	1.041	1.583	0.256	0.598	0.299	0.493	0.548 to 1.534
VS	**IL**	**1,800**	**73**	0.743	2.799	0.015	0.625	0.073	0.121	0.623 to 0.864

Continued										
Speed Control	Pump Class	Nominal Speed	n	Average	Max	Min	Std Dev	Standard Error	90% Margin of Error	90% Confidence Interval
VS	**IL**	**3,600**	**3**	1.162	1.212	1.076	0.075	0.043	0.071	1.09 to 1.233
VS	**ST**	**3,600**	**1**	1.634	1.634	1.634	0.000	-	-	1.634 to 1.634
VS	**RSV**	**1,800**	**11**	0.732	1.261	0.266	0.383	0.115	0.190	0.542 to 0.923
VS	**RSV**	**3,600**	**7**	1.180	1.973	0.737	0.479	0.181	0.299	0.881 to 1.479
VS	**ST**	**1,800**	**2**	1.942	2.571	1.314	0.889	0.629	1.037	0.905 to 2.979

Table 45: RTF Assumed Adjustment Factors

Pump Class and Nominal Speed	RTF Assumptions	
	Constant Speed	Variable speed
ESCC,1800	0.85	1.13/1.22
ESCC,3600	0.85	1.13/1.22
ESFM,1800	0.85	1.13/1.22
ESFM,3600	0.85	1.13/1.22
IL,1800	0.85	1.13/1.22
IL,3600	0.85	1.13/1.22
RSV,1800	0.85	1.13/1.22
RSV,3600	0.85	1.13/1.22
ST,1800	1.15	1.5/1.6
ST,3600	1.15	1.5/1.6

Figure 15 shows that the difference between the Adjustment Factor pumps of the same class but different nominal speeds are not variable enough to justify separating by nominal speed. While differences between ST and other pump classes were evident at this granularity, the team felt that the small sample size may be impacting the averages.

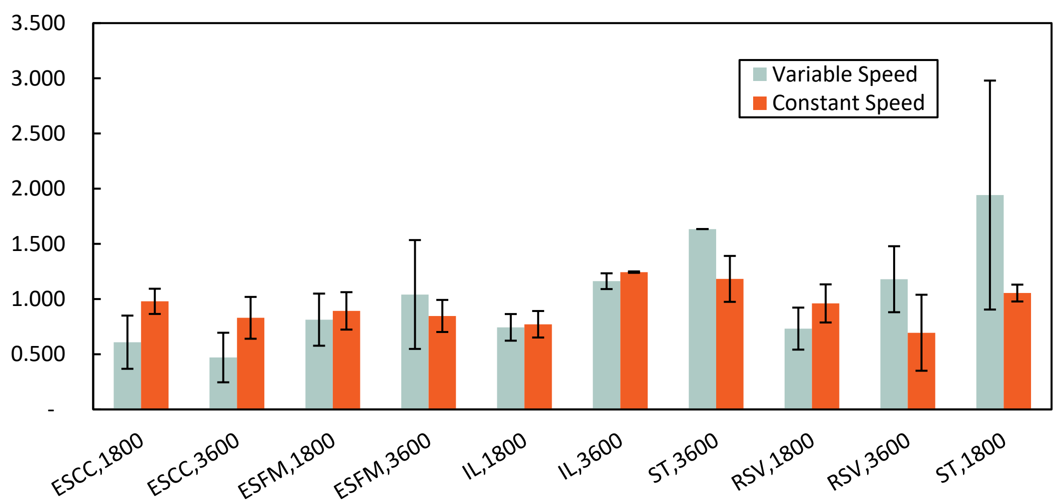

Figure 15: Adjustment Factor by Pump Class and Nominal Speed

When combined into Pump Class-level Adjustment Factors, as they are in Figure 16, the difference between ST pumps and all other pump classes is still present, with significant variability in the variable speed ST pumps. However, the same pattern is evident, with less variability, in the agricultural pumps when Adjustment Factor is aggregated by sector (shown in Figure 17).

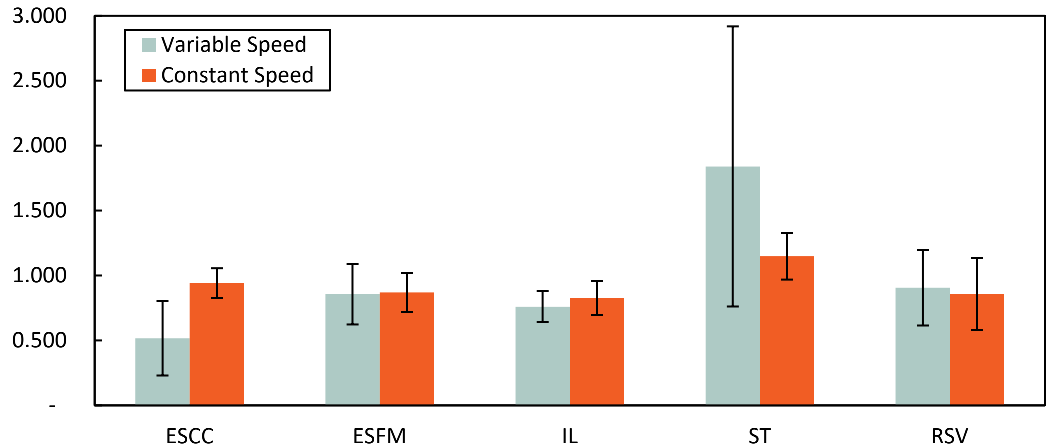

Figure 16: Adjustment Factor by Pump Class

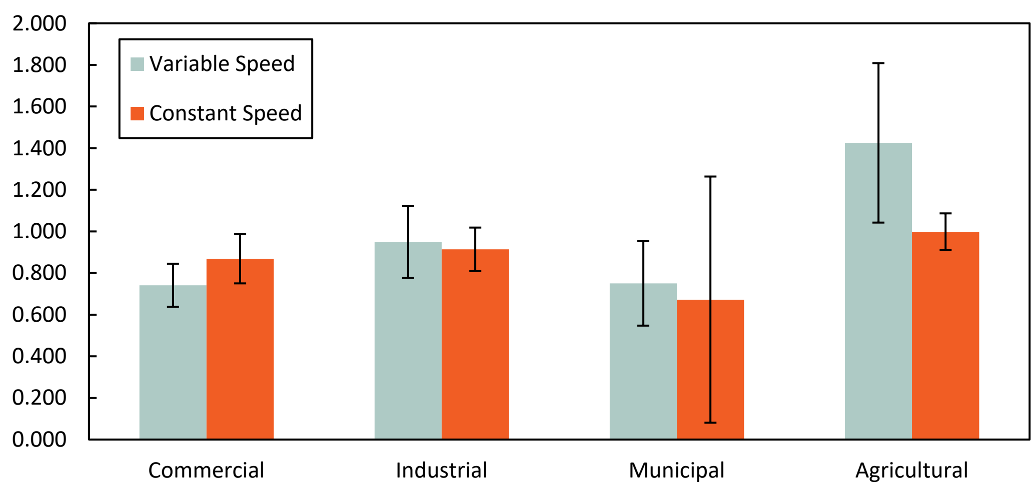

Figure 17: Adjustment Factor by Sector

The affect that separating ST from the other pump classes has on the accuracy of the average Adjustment Factor is show in Table 46, which compares two things: 1) the a percent different a speed control specific Adjustment Factor (i.e., a VS Adjustment Factor and a CS Adjustment Factor) is to the Pump Class and Nominal Speed average Adjustment Factor and 2) the percent different a speed control specific Adjustment Factor with separate Factors for ST Pumps is to the Pump Class and Nominal Speed average Adjustment Factor. The RMS for the separated Adjustment Factors is 23%, compared to the 30% for the speed control Adjustment Factor. The Max and Min percent difference range is 30 percentage points smaller for the separated Adjustment Factor.

Table 46: Observed Adjustment Factor, Disaggregated

Statistic	Percent Difference from Average Observed Adjustment Factor by Pump Class and Nominal Speed	
	Speed Control Adjustment Factor	Adjustment Factor with ST separated
Sample Size	20	20
Root Mean Square	30%	23%
Max % Difference	71%	66%
Min % Difference	-59%	-34%

4.3.2.2 Adjustment Factor Sub-Factor

As presented previously in Section 4.1.2.2, the variations in Adjustment Factor are dependent on how the pump and motor are installed and the operating characteristics of the pump (referred to in this report as "Sub-Factors"). The research team investigated the impact of these individual variables on the calculated Adjustment Factor. Those variables include motor oversizing, load profile, offset from BEP, and static head.

4.3.2.2.1 Motor Oversizing

The research team initially investigated motor oversizing for all the pumps submitted to the research. A total of 282 pumps are included in this analysis. Motor oversizing is calculated by comparing the motor HP from the motor nameplate to the pump input power at BEP (Pump HP), where the Pump HP is calculated as:

$$PumpHP_{BEP} = \frac{Flow_{BEP} * Head_{BEP}}{3960 * \eta_{pump}} \quad (15)$$

where

$PumpHP_{BEP}$ = Pump input power at BEP, HP
$Flow_{BEP}$ = Flow at BEP, gpm
$Head_{BEP}$ = Head at BEP, ft
η_{pump} = Pump efficiency

The percent motor oversizing is then calculated as the ratio of the Motor HP to the Pump HP at BEP minus 1, as shown in the following equation:

$$Motor\ Oversizing\ (\%) = \frac{MotorHP}{PumpHP_{BEP}} - 1 \quad (16)$$

where

$MotorHP$ = Nameplate motor HP
$PumpHP_{BEP}$ = Pump input power at BEP, HP

Figure 18 shows all the percent motor oversizing plotted against each pump's motor HP. There is one outlier that stands out in this data with a motor oversizing of 239%. The data submission form for this pump indicates that the pump owner trimmed the pump impeller from 12" to 9" after installation, which caused the abnormally high motor oversizing. When the pump HP is calculated with a 12" impeller diameter the motor is only 29% oversized. This pump was removed from the subsequent analysis. The straight average motor oversizing for all pumps in the sample is 24%. Table 47 lists the statistics associated with this value.

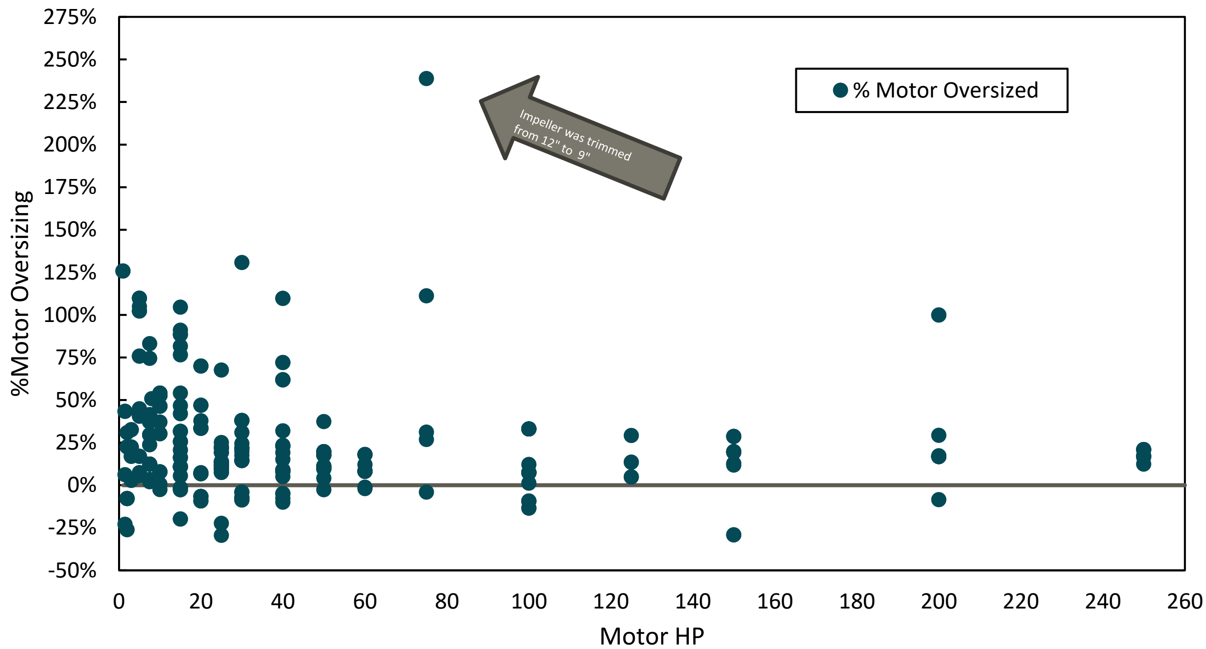

Figure 18: Percent Motor Oversizing vs Motor HP

Table 47: Percent Motor Oversizing Statistical Analysis

Statistic	All Pumps without Outlier
No. of Pumps in the sample	282
Average	24%
Max	131%
Min	-59%
Standard Deviation	30%
Standard Error	1.8%
90% Margin of Error	3%
90% Confidence Interval	21% to 27%

When the research team investigated the motor oversizing averaged by motor HP bin, it is apparent that the motor oversizing has a slight dependence on motor HP where the motor HP decreases as the motor oversizing increases. This is most likely a function of the fact that the same discrete difference in motor and pump power has a larger impact on the percent oversizing for smaller systems. In addition, the higher cost of larger motors may also discourage customers from dramatically oversizing motors on larger pump systems. To keep the sample sizes reasonable in this analysis, the research team aggregated the pumps into six motor HP bins with approximately the same sample size. This minimizes the effect of noise in the data and allows the team to develop meaningful statistics for each HP bin. Table 48 and Figure 19 show the average motor oversizing and statistics for each bin.

Table 48: Motor Oversizing Statistical Analysis, grouped by Motor HP

Motor HP Range	n	Average % Oversized	Max	Min	Standard Deviation	Standard Error	90% Margin of Error
0 - 5 Motor HP	39	34%	126%	-59%	45%	7%	12%
5 - 10 Motor HP	39	32%	83%	-3%	22%	4%	6%
10 - 25 Motor HP	68	23%	104%	-30%	29%	4%	6%
25 - 50 Motor HP	62	23%	131%	-10%	29%	4%	6%
50 - 100 Motor HP	39	12%	111%	-14%	21%	3%	6%
100 - 250 Motor HP	35	19%	100%	-29%	24%	4%	7%

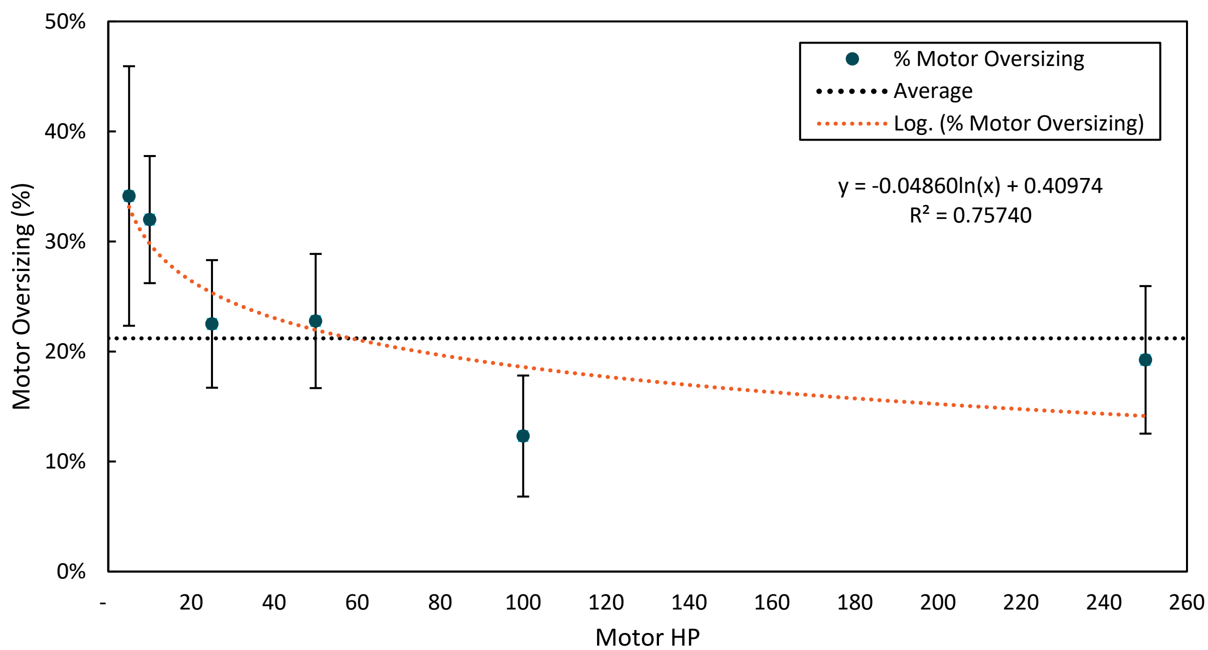

Figure 19: Percent Motor Oversizing vs Motor HP, by Motor HP Bin

Figure 19 also illustrates the trend observed between motor oversizing and motor HP. The trend appears to present a logarithmic relationship, as shown in Equation 17, with an overall R-squared value of 0.757.

$$Motor\ Oversizing = -0.04860 * \ln(MotorHP) + 0.40974 \tag{17}$$

The research team also investigated motor oversizing in relation to the pump class. The RTF measures established a different Adjustment Factor for ST Pumps because submersible motors have a service factor of 1.2 instead of 1.0 (for non-submersible turbine). The RTF, using anecdotal accounts from manufacturers, developed different Adjustment Factors to compensate for this. From these data, it appears that motor sizing practices are consistent across pump types.

Table 49 shows that the full-sample average motor oversizing of 24% falls within the 90% interval for all pump classes apart from Inline, which is has the largest motor oversizing at 30%. The collected data does not support the assumption made by the RTF that the Adjustment Factor for ST pumps is higher due to greater motor oversizing. From these data, it appears that motor sizing practices are consistent across pump types.

Table 49: Average Motor Oversizing, by Pump Class

Pump Class	ESCC	ESFM	IL	RSV	ST
Number of Pumps	43	57	118	36	24
Average % Oversized	**16%**	**25%**	**30%**	**19%**	**12%**
Max	131%	88%	126%	105%	111%
Min	-59%	-30%	-20%	-14%	-29%
Standard Deviation	36%	26%	28%	24%	38%
Standard Error	5%	3%	3%	4%	8%
90% Margin of Error	9%	6%	4%	7%	13%
90% Confidence Interval	7% to 25%	20% to 31%	26% to 34%	12% to 25%	-1% to 25%

4.3.2.2.2 Static Head

The static head in a pumping system is the amount of pressure that the pump must overcome in order to initiate flow in the pump system. DOE's analysis and the PEI metric assume a static head value equal to 20% of head at BEP for all pumps. This assumption, coupled with the point which the pump operates on the pump curve (referred to in this analysis as BEP Offset), allowed DOE to model the system curve for variable speed pumps. The RTF modified DOE's analysis to use different minimum static head values for each application, as discussed in Section 4.2.1.

To investigate the static head assumptions the RTF made, the research team reviewed the head vs flow charts for each pump collected and identified the variable speed pumps that operate down the system curve.[43] The minimum static head in a pump system can only be identified on variable speed pumps that clearly operate along system curve, with no other mechanical or control-related features that would hold the pressure of the pump above the minimum static requirement of the system.

The research team identified 52 variable speed pumps operating down the system curve. To analyze the head curve for each of these pumps, first the head at BEP was calculated using the flow at BEP, along with the 2nd order polynomial equation developed to model the head vs flow curve. Then, the minimum static head was calculated as the smallest annualized head value recorded for the pump divided by the head at BEP, as shown in Equation 18:

[43] Engineering judgment was used, along with the distance the flow values were away from the pumps minimum flow requirement.

$$Minimum\ Static\ Head = \frac{Smallest\ Annualized\ Head\ Value}{Head\ at\ BEP} \tag{18}$$

where

Minimum static head	=	Static Head, as percent of Head at BEP
Smallest Annualized head Value	=	Smallest, non-zero head value in the annualized data, ft of H_2O
Head at BEP	=	Calculated Head at BEP, ft of H_2O

The average static head for all 52 identified pumps was calculated at 31% of head at BEP, shown in Table 50. This value falls directly between the two values for static head set by the RTF (20% for Industrial and Municipal and 40% for Commercial HVAC and DHW).

Table 50: Average Static Head, All Pumps

Statistic	All Pumps, Observed
No. of Pumps in the sample	52
Average, as Percent of Head at BEP	31%
Max	90%
Min	0.01%
Standard Deviation	25%
Coefficient of Variation	0.81
Standard Error	3%
90% Margin of Error	6%
90% Confidence Interval	25% to 37%

When disaggregated by RTF application, as it is in Table 51, the values for static head fall even closer to the RTF estimates. The observed Commercial HVAC and DHW pumps have a static head of 35% of head at BEP and Industrial and Municipal have a static head of 22% of head at BEP. Both these values, if rounded to the nearest tens place, would equal the estimate made by the RTF. The research team disaggregated the pumps by research application to investigate any relationship within the RTF Applications. There were differences in the static head between each research application, however, the research team felt that the small sample sizes at this level of granularity decreased the significance of the average minimum static heads observed. As Table 52 shows, 5/7 of the research applications have a sample size less than 10, and only one research application has a sample size greater than 20.

Table 51: Average Static Head, by RTF Application

Statistic	Commercial HVAC and DHW	Industrial and Municipal
No. of Pumps in the sample	34	18
Average, as Percent of Head at BEP	35%	22%
Max	90%	87%
Min	1%	0%
Standard Deviation	22%	28%
Standard Error	4%	7%
90% Margin of Error	6%	11%
90% Confidence Interval	29% to 42%	12% to 33%

Table 52: Average Static Head, by Research Application

Statistic	Commercial Cooling	Commercial Cooling Tower	Commercial Heating	Commercial Pressure Boost	Industrial	Municipal
n	22	7	2	3	7	11
Average, as % of Head at BEP	29%	54%	46%	32%	46%	8%
Max	90%	71%	55%	74%	87%	16%
Min	1%	26%	37%	10%	0%	4%
Standard Deviation	20%	23%	13%	36%	0.33	0.04
Coefficient of Variation	0.70	0.42	0.28	1.12	0.74	0.48
Standard Error	4%	9%	9%	21%	13%	1%
90% Margin of Error	7%	14%	15%	35%	21%	2%
90% Confidence Interval	22% to 36%	40% to 69%	31% to 61%	-2% to 67%	25% to 66%	6% to 9%

The research team feels the most robust disaggregation of static head is at the RTF-Application level. While the standard deviation and standard error are slightly higher at this level (compared to the full sample average), neither average static head value falls within the 90% confidence interval of the other.

As the observed static head values generally agree with the original RTF assumptions, these new values should not dramatically affect the updated Adjustment Factor values as compared to the original RTF planning estimates.

4.3.2.2.3 Load Profile

The Adjustment Factor compensates for the difference between the Load Profile assumed in the calculation of PEI and the real-world load profile. The main tenet of speed control method is that variable speed pumps are able to operate at multiple driver shaft speeds, allowing the load profile to more easily be tailored to the system[44]. This led the research team to first investigate the load profile of all pumps, then the load profile of pumps segregated by speed control method and application.

Figure 20 show the load profile for all pumps in the research that were submitted with operational data and known BEP. The operating time varies between 15% and 30% across the load points from 25%-100% of BEP flow. The data shows that approximately 15% of the operating time is spent above 100% BEP flow. Table 53 provides the statistical analysis for each load point. The research team uses this high-level view of load profile as a comparison to the load profiles when disaggregated by speed control method.

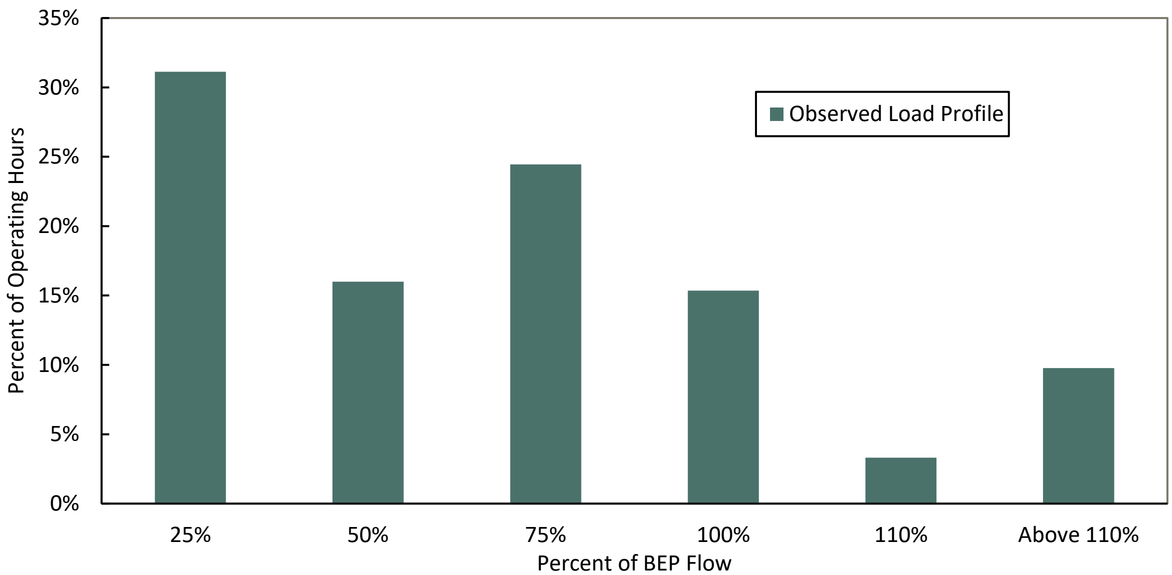

Figure 20: Observed Load Profile, All Pumps

Table 53: Observed Load Profile Statistical Analysis

Load Point	25%	50%	75%	100%	110%	Above 110%
Percent of Operating Hours	31%	16%	24%	15%	3%	10%
No. of Pumps in Sample	178	178	178	178	178	178
Standard Deviation	45%	31%	38%	33%	15%	28%
Standard Error	3%	2%	3%	2%	1%	2%
90% Margin of Error	6%	4%	5%	4%	2%	3%

Figure 21 and Figure 22 show the load profile for all constant speed pumps and for all variable speed pumps, respectively. These figures also show the average RTF Load Profile for each speed control method. For both constant and variable speed pumps the RTF established four load profiles, with probability of

[44] This is not implying that it is not possible to vary operating points when not a variable speed pump, but that it is more likely to occur when the pumping system is designed with equipment that can efficiently vary the load point without sacrificing performance.

occurrences for each. The average RTF load profiles shown here represent the weighted average of the four established load profiles.

For constant speed pumps the observed load profile spends more time above 100% of flow at BEP than the RTF's assumption predicts. The RTF also estimates that a large amount of time is spent at 100% of BEP. The observed load profile is more evenly distributed than the RTF assumed, with a significant number of hours spent at 75 and 100% of BEP flow. This demonstrates that there may have been overconfidence in the "right-sizing" of constant speed pumps in the original assumptions. In the load profiles established by the RTF all four estimate at least 50% of a pumps operating time spent at 100% BEP, with one load profile (weighted at 30% probability) where 100% of the time is spent at 100% of BEP. Conversely, the RTF does not assume any time is spent above 110% of BEP, and the observed operation shows 23% of the time is spent at this load point. 15% of the pumps in the constant speed sample spend 100% of their operating time above 110% of BEP. Of these pumps only 2 operate above 150% of BEP. This sizing practice is not unreasonable as viable operating regions are present both above and below the BEP on typical pump curves and small pumps may be less expensive than similar pump designed to handle more head and flow. When discussed with pump manufacturers, it was noted that at least one manufacturer, when sizing pumps, sizes them to operate above BEP so when turned down the efficiency is heading towards BEP instead of away from it.

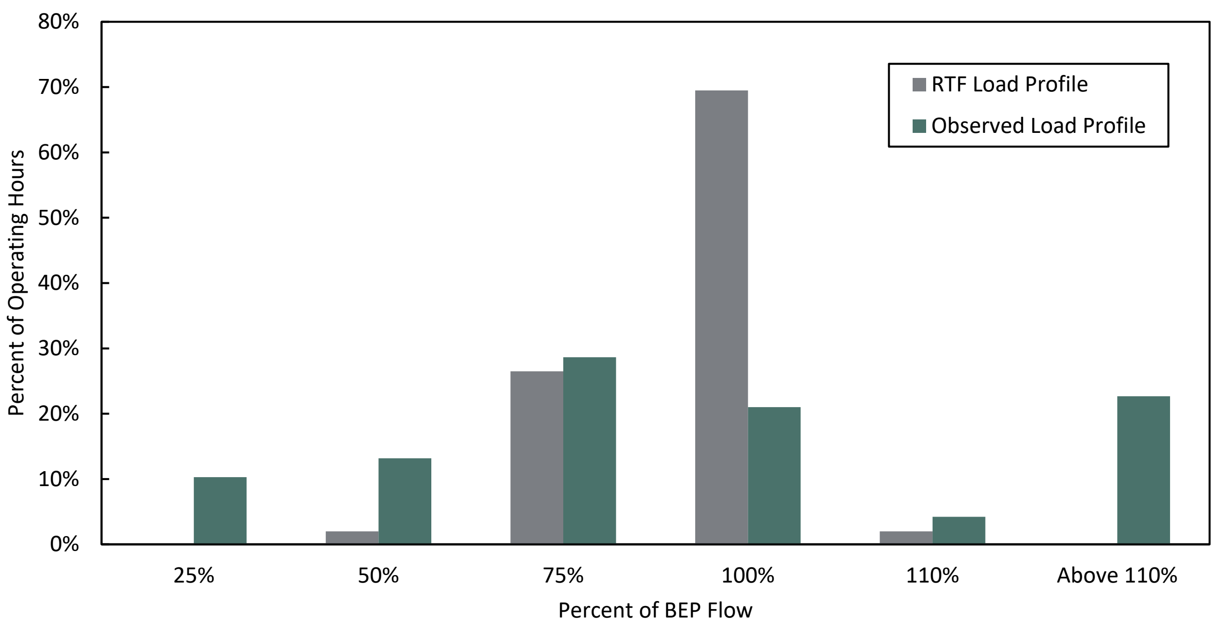

Figure 21: Constant Speed Load Profile, Observed and RTF Estimated

The observed load profile for variable speed pumps in Figure 22 is also more evenly distributed between 50% - 100% of BEP flow than the RTF estimated. There is drastically more operation at 25% of BEP and less operation at 100% of BEP in the observed load profile than the in the RTF estimate. Similar to constant speed pumps, there is more operation above BEP in the observed load profile with 8% of the pumps in the variable speed sample operating any amount of time above 110% BEP.

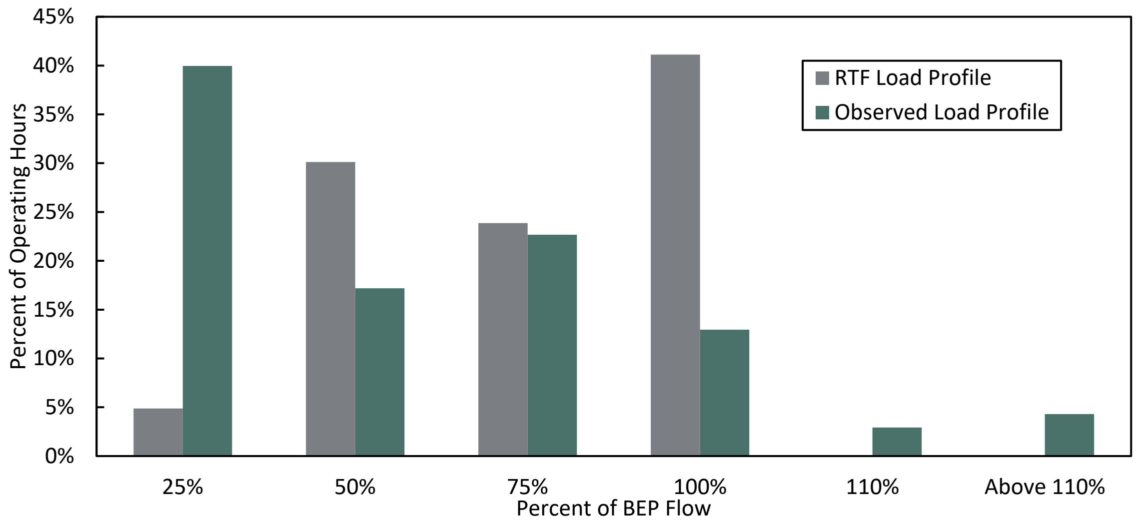

Figure 22: Variable Speed Load Profile, Observed and RTF Estimated

The statistical analysis for the load profiles, disaggregated by speed control method are shown in Table 54 and

Table 55. With multiple load points for each load profile, comparing the accuracy of an application- or sector-specific load profile to the aggregated load profile is difficult and requires some judgement (e.g., certain load points may be more accurate in one load profile while other load points are less accurate). For the constant speed load profile, the standard deviations range from 17% to 42% for the constant speed load profile (different standard deviation values for each load point). The standard deviation spans from 14% to 47% for the variable speed load profile. When compared to the range of standard deviations of the all-pump load profile (18% to 39%) the spread is larger for the constant speed load profile. A similar pattern is seen with the standard error. When the average standard error is calculated across all 6 load points, weighted for the amount of time spent at each load point, the standard error for the full sample load profile is 2.7%, while the standard error for the constant speed case is 5.1%, and 3.63% for the variable speed load profile.

Table 54: Statistical Analysis, Constant Speed Load Profile

Load Point	25%	50%	75%	100%	110%	Above 110%
Percent of Operating Hours	10%	13%	29%	21%	4%	23%
No of pumps in sample	53	53	53	53	53	53
Min	0%	0%	0%	0%	0%	0%
Max	100%	100%	100%	100%	100%	100%
Standard Deviation	30%	32%	42%	38%	17%	41%
Standard Error	4%	4%	6%	5%	2%	6%
90% Margin of Error	7%	7%	10%	9%	4%	9%

Table 55: Statistical Analysis, Variable Speed Load Profile

Load Point	25%	50%	75%	100%	110%	Above 110%
Percent of Operating Hours	40%	17%	23%	13%	3%	4%
No of pumps in sample	125	125	125	125	125	125
Min	0%	0%	0%	0%	0%	0%
Max	0%	0%	0%	0%	0%	0%
Standard Deviation	47%	31%	36%	30%	14%	18%
Standard Error	1.18	1.80	1.58	2.30	4.72	4.22
90% Margin of Error	4%	3%	3%	3%	1%	2%

The next level of disaggregation the research team performed was to explore if a relationship existed between the load profile and the sector the pump is installed in. Figure 23 and Figure 24 display the speed control and sector-specific load profiles compared to each other. Table 56, Table 57, and Table 58 show the speed control-load profiles and statistical analysis for the commercial, industrial, and municipal sector, respectively.

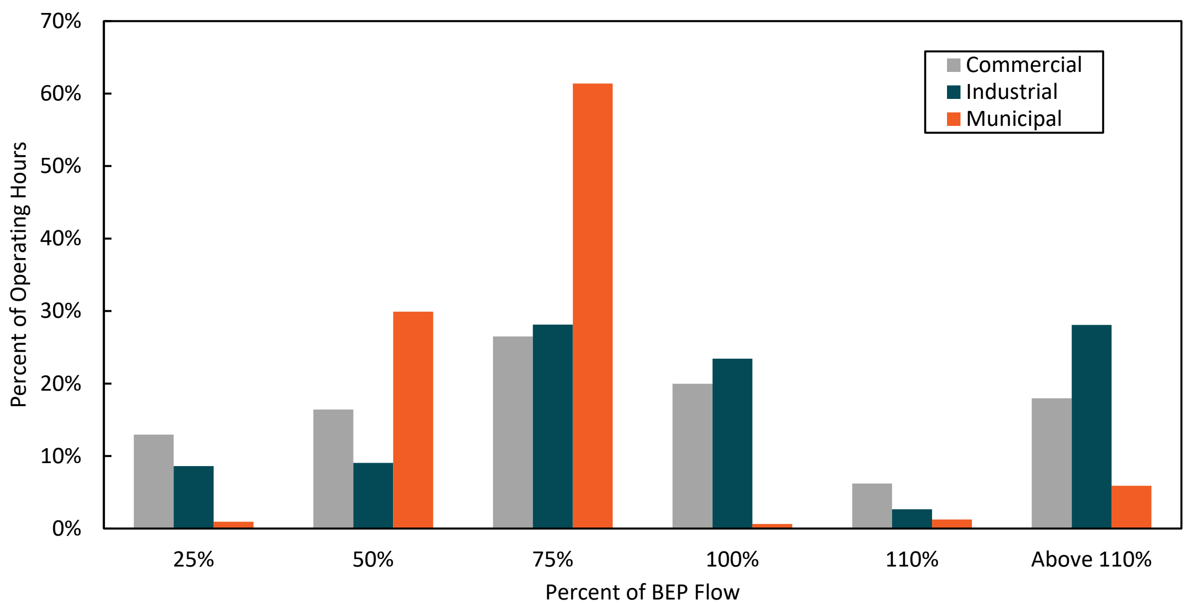

Figure 23: Constant Speed Load Profile, by Sector

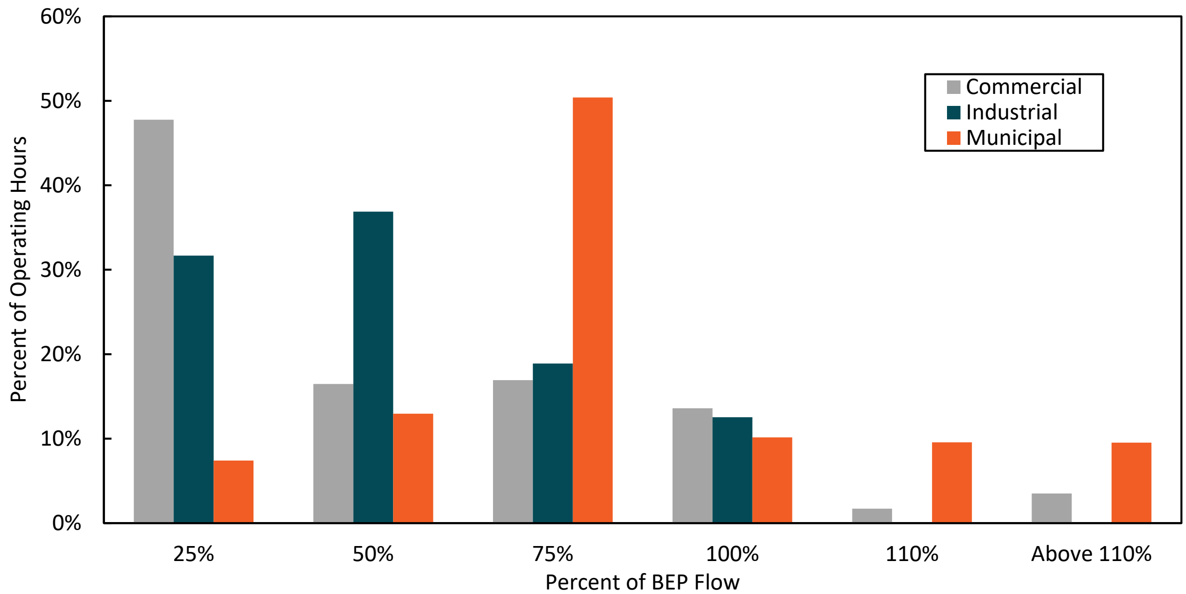

Figure 24: Variable Speed Load Profile, by Sector

Table 56: Statistical Analysis, Commercial Load Profile

	Count	25%	50%	75%	100%	110%	Above 110%
Constant Speed	**24**	**13%**	**16%**	**26%**	**20%**	**6%**	**18%**
Standard Deviation		3%	34%	37%	42%	38%	21%
Standard Error		1%	7%	8%	9%	8%	4%
90% Margin of Error		2%	11%	12%	14%	13%	7%
Variable Speed	**96**	**48%**	**16%**	**17%**	**14%**	**2%**	**4%**
Standard Deviation		35%	48%	31%	31%	30%	7%
Standard Error		4%	10%	6%	6%	6%	1%
90% Margin of Error		7%	16%	11%	10%	10%	2%

Table 57: Statistical Analysis, Industrial Load Profile

	Count	25%	50%	75%	100%	110%	Above 110%
Constant Speed	**32**	**9%**	**9%**	**28%**	**23%**	**3%**	**28%**
Standard Deviation		28%	21%	44%	41%	14%	46%
Standard Error		5%	4%	8%	7%	2%	8%
90% Margin of Error		8%	6%	13%	12%	4%	14%
Variable Speed	**14**	**32%**	**37%**	**19%**	**13%**	**0%**	**0%**
Standard Deviation		46%	42%	37%	38%	0%	0%
Standard Error		12%	11%	10%	10%	0%	0%
90% Margin of Error		20%	19%	16%	17%	0%	0%

Table 58: Statistical Analysis, Municipal Load Profile

	Count	25%	50%	75%	100%	110%	Above 110%
Constant Speed	**4**	**1%**	**30%**	**61%**	**1%**	**1%**	**6%**
Standard Deviation		1%	18%	31%	1%	2%	8%
Standard Error		1%	9%	15%	0%	1%	4%
90% Margin of Error		1%	15%	25%	1%	1%	7%
Variable Speed	**24**	**7%**	**13%**	**50%**	**10%**	**10%**	**10%**
Standard Deviation		23%	22%	44%	28%	30%	30%
Standard Error		5%	4%	9%	6%	6%	6%
90% Margin of Error		8%	7%	15%	9%	10%	10%

Figure 23 and Figure 24 show that there are both similarities and differences in the load profiles among the sectors. For example, the pattern of more turndown (more time spent at lower flow rates) in the variable speed pumps is consistent across the sectors. However, there amount of turndown varies significantly among the sectors. For both variable and constant speed pumps, municipal pumps spend a majority of operating hours between 75% and 100% of flow at BEP. This could be because the pumps in municipal facilities are often very large, and more time is spent "right-sizing" the pump to the load due to the high cost of the large pumps. Conversely, commercial pumps spend the most time at or below 25% of BEP flow, which could be caused by both the need to turn down the system to meet variable HVAC loads, or more extreme oversizing for smaller commercial pumps, which necessitates operating at lower flows to conform to system requirements. The industrial load profile is in between the municipal and commercial load profiles, with the majority of hours occurring at 75 and 100% of BEP flow for constant speed pumps, but significant hours spent at 25 and 50% of BEP flow for variable speed pumps.

In general, the observed load profiles, which feature higher number of operating hours at lower flow rates than originally assumed in the RTF and DOE analysis, will result in lower Adjustment Factors and lower pump energy consumption as compared to the Planning measures. This is particularly true for variable speed pumps, which have a stronger relationship between flow rate and input power than constant speed pumps.

4.3.2.2.4 BEP Offset

The final sub-factor affecting the Adjustment Factor (and the relationship between the calculated energy consumption and the real-world observed energy consumption) is BEP Offset. BEP Offset describes where on the full speed pump curve the pump operates, with respect to BEP. The RTF and DOE both assumed that all pumps operate between -25% and +10% of BEP on the full speed pump curve.

The research team analyzed BEP Offset by first calculating the maximum observed flow rate for all pumps that had annualized flow values, as well as the flow at BEP. The BEP Offset is then calculated as a ratio of the maximum observed flow and the flow at BEP. Table 59 shows the average BEP offset for all pumps in the sample, calculated at -17%. The histogram in Figure 25 shows that the distribution of BEP Offset is relatively normal, with a slight skew towards the left of BEP values (below zero). The data show a 90% confidence interval of -22 and -12% of BEP.

Table 59: Average BEP Offset and Statistical Analysis, All Pumps

Statistic	All Pumps, Observed
No. of Pumps in the sample	176
Average BEP Offset	-17%
Max	82%
Min	-98%
Standard Deviation	39%
Standard Error	3%
90% Margin of Error	5%
90% Confidence Interval	-22% to -12%

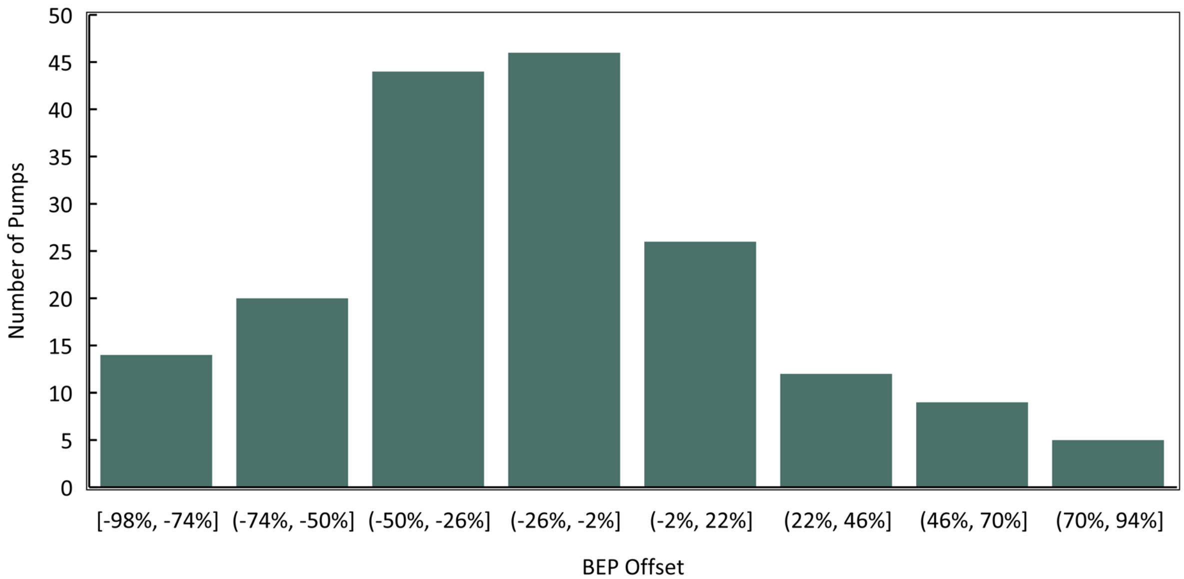

Figure 25: Histogram of BEP Offset, as a Percent of BEP

The RTF used the same assumption as DOE, keeping BEP Offset set as a range between -25% and +10%. This range covers 31% of the sample analyzed in this research. If the span of these values is changed to -76% to +52%, the range covers 90% of the sample.

The research team also looked at BEP Offset in relation to the speed control method. Table 60 shows that the average BEP Offset for both speed control methods are within each other's 90% confidence interval, as well as the 90% confidence interval of the full sample average. This indicated to the research team that there is not a significant difference between the BEP Offset values when disaggregated by speed control method.

Table 60: Average BEP Offset and Statistical Analysis, by Speed Control Method

Statistic	Constant Speed, Observed	Variable Speed, Observed
No. of Pumps in the sample	52	124
Average BEP Offset	-14%	-19%
Max	60%	82%
Min	-98%	-92%
Standard Deviation	38%	39%
Standard Error	5%	4%
90% Margin of Error	9%	6%
90% Confidence Interval	-22% to -5%	-24% to -13%

In general, a lower BEP Offset should result in slightly lower Adjustment Factors for both constant and variable load pumps, since the max speed point will be slightly lower than the PEI test procedure assumes and, therefore, the pump power will be slightly lower than at the 100% of BEP value. However, the impact of BEP Offset is minor compared to the impact of the other sub-factors.

4.3.2.3 Adjustment Factor Summary

The Adjustment Factor is dependent on several variables that impact the real-world power consumption of pumps in different applications. The variables considered here include: static head, BEP Offset, Load Profile, and Motor Oversizing. Of these, static head, BEP Offset, and Load Profile all describe the different operating points the pump operates at, as compared to the DOE and RTF assumptions. These factors are somewhat intertwined in their impact on the overall Adjustment Factor and pump energy use (e.g, the BEP Offset variable will also impact the observed load profiles). As such, they should be treated together as a single “load profile” Adjustment Factor. The previous analysis, as summarized in Table 61, shows that this load profile Adjustment Factor is dependent on application and speed control case.

Table 61: Summary of Adjustment Factor Sub-Factors and Dependencies

<table>
<tr><th>Adjustment Factor</th><th>Sub-Factor</th><th>Dependencies</th><th>Overall Dependencies</th></tr>
<tr><td rowspan="3">Load Profile</td><td>Static Head</td><td>RTF Application</td><td rowspan="3">RTF Application and Speed Control Case</td></tr>
<tr><td>Load Profile</td><td>RTF Application and Speed Control Case</td></tr>
<tr><td>BEP Offset</td><td>None</td></tr>
<tr><td>Motor Oversizing</td><td>Motor Oversizing</td><td>Horsepower</td><td>Horsepower</td></tr>
</table>

For Motor Oversizing, the research team presented information in Table 49 that did not support the assumption the RTF made in regards to separate sizing practices for submersible motors. Using this information, the analysis presented a relationship between motor oversizing and motor HP. The team developed a separate equation to describe how this factor varies with Motor HP that can be applied to the energy consumption model to isolate the impact of Motor Oversizing on the overall energy consumption. Equation 17 shows the relationship between motor oversizing and Motor HP. The research team used this equation to calcualte Motor Oversizing Factors for 6 different Motor HP Ranges, shown in Table 62.

Table 62: Motor Oversizing Factor, by Motor HP Bins

Motor HP Range	Representative HP	Number of Pumps	Motor Oversizing Factor
0 - 5 Motor HP	**3**	32	0.3652
5 - 10 Motor HP	**8**	31	0.3118
10 - 25 Motor HP	**20**	48	0.2641
25 - 50 Motor HP	**35**	46	0.2370
50 - 100 Motor HP	**75**	32	0.1999
100 - 250 Motor HP	**150**	21	0.1662

This factor can then be applied directly to the Energy Consumption Model to calculate energy consumption for a given pump:

$$Energy_{pump} = HP * 0.746 * (1 - Factor_{MO,HP}) * OpHrs_A * PEI * Factor_{Adj,A,SC} \quad (19)$$

where

$Energy_{pump}$	=	Annual Pump Energy Consumption, kWh
HP	=	Motor Horsepower (input)
$Factor_{MO,HP}$	=	Motor Oversizing Factor, varies based on Motor HP as shown in Table 62
$OpHrs_A$	=	Operating Hours, varies based on Application (A)
PEI	=	PEI (input)
$Factor_{Adj,A,SC}$	=	Load Profile Adjustment Factor, varies based on Application (A) and Speed Control Case (SC)

The initial Adjustment Factor analysis showed variation in Adjustment Factor for ST pumps and agricultural pumps. All ST pumps are in the agricultural sector, so the variation being consistent between the two factors is logical. The motor oversizing analysis presented in Section 4.3.2.2.1 indicates this variation is not a pump class-dependent factor, so the research team infers that the operating characteristics and load profile specific to the agricultural sector is driving up the Adjustment Factor.

As shown in equation 19 and described previously, the Load Profile Adjustment Factor varies most significantly based on RTF application and speed control case. Separating the Load Profile Adjustment Factor by application allows for this Adjustment Factor to account for the differences in Adjustment Factor seen in Figure 16 and Figure 17.

The final Load Profile Adjustment Factors are listed in Table 63.

Table 63: Final Load Profile Adjustment Factors, by Application and Speed Control Case

Application	Constant Speed	Variable speed
Agricultural	1.325	1.845
Commercial	1.250	1.000
Industrial	1.310	1.214
Municipal	0.840	0.990

The Load Profile Factors listed in Table 63 represent the differences between the actual weighted average power consumption and the PEI-estimated weighted average power consumption, accounting for the impact of the actual load profile, static head, and BEP offset on the actual the power consumption.

For constant speed pumps the commercial and industrial load profiles, the load profile factors for agricultural, commercial, and industrial sectors are all higher than 1.000. In these sectors, pumps have more than 25% of their operating hours above 100% flow at BEP, which was not captured in the load profiles used by the RTF, leading to the higher-than-estimated actual energy consumption. Municipal pumps, however, spend the majority of their time at 75% flow at BEP, which is slightly lower than the RTF's assumed load profile. This causes the municipal energy consumption to be lower than that assumed by the RTF (which assumed more operation at 100% of BEP flow) and the Load Profile Factor to be lower than 1.000.

A similar trend is seen with variable speed municipal pumps, where the low Load Profile Factor is adjusting for the time the pump spends at 75% flow at BEP, resulting in an adjustment factor that is lower than 1.000. The commercial and industrial Load Profile Factors are less intuitive. The load profiles for these pumps are weighted around 25% and 50% flow at BEP but the Factors are equal to or larger than 1.000. The static head and BEP offset may be contributing to these factors being higher than 1.000, with either higher static head increasing the energy used at lower flow rates and/or a more negative BEP Offset value driving the system curve and energy consumption up at lower flow rates (i.e., if the BEP offset is below 100% BEP flow, 100% speed will occur at a "reduced" flow rate with respect to BEP, which will result in higher speeds at lower flow rates across the operating range of the pump).

Figure 26 shows two system curves that graphically represent the increase in power consumption due to BEP offset. System Curve 1 crosses the pump curve at BEP. When the system curve crosses the pump curve at a lower flow rate than BEP (which represents a pump with BEP offset less than 100%), as System Curve 2 does, the power used at those lower flow rates is higher than it would be with BEP Offset closer to 100%.

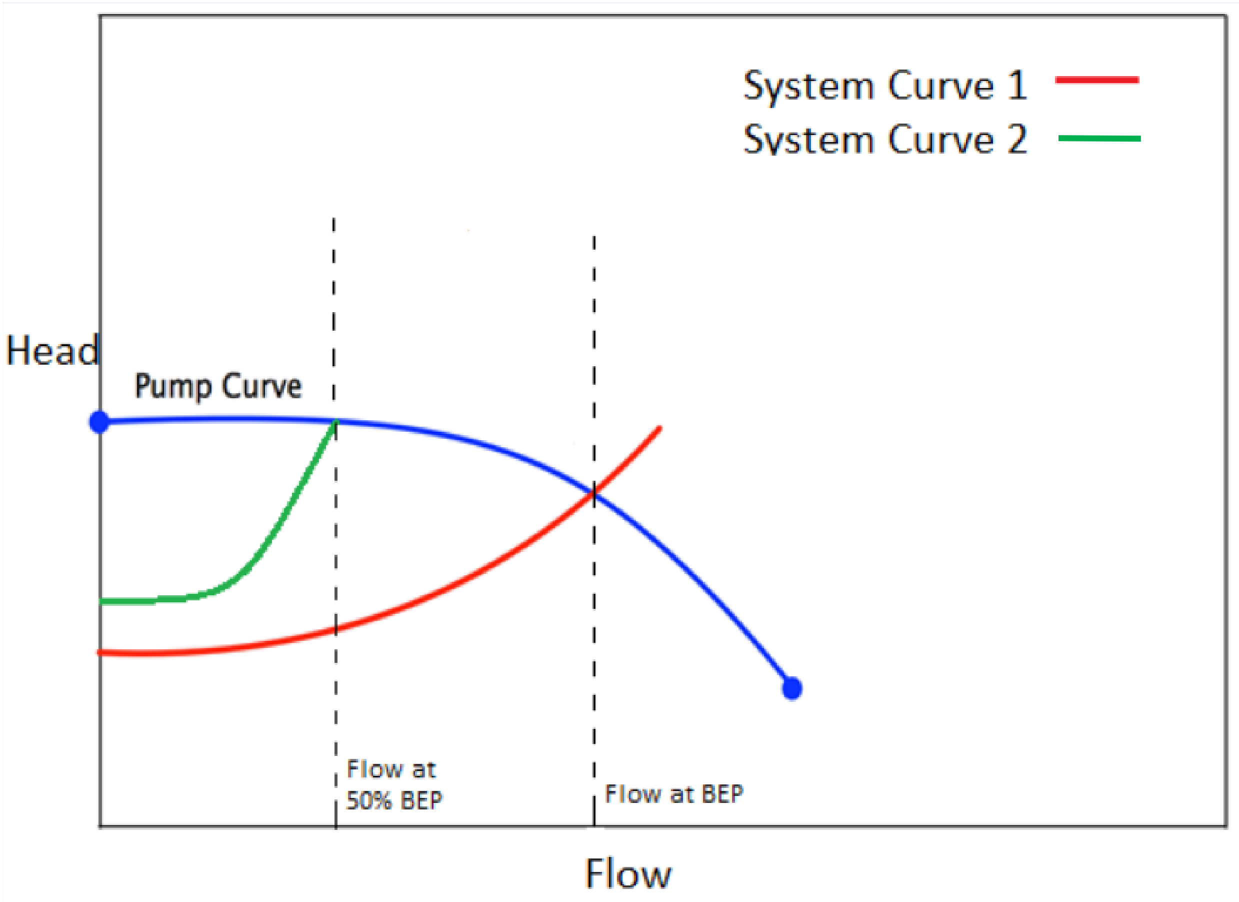

Figure 26: BEP Offset, Graphical Representation

5 Circulator Research

Circulators are a specific type of clean water pump design for use in hydronic heating and domestic hot water recirculation applications. As discussed in Section 2, DOE specifically excluded Circulators from the Final Rule covering Clean Water Pumps because of their unique design and specific application. DOE's established a Working Group to develop a test procedure and standards recommendations for Circulators. This Working Group published consensus recommendations for Circulators in 2016.[45] Since January of 2017 DOE's standards program has slowed its work considerably and has not published a Final Rule establishing energy conservation standards for Circulators. Despite no federal standards for Circulators, the Hydraulic Institute proceeded to develop a rating program for Circulators,[46] based on the Working Group's recommendations. The UES Measures established by the RTF rely on the Working Group recommendations as well. This Section describes the RTF's UES Measures, the research performed to validate these measures, and the analysis and results from that research.

5.1 RTF Unit Energy Savings Measures

The RTF's UES Measures for Circulators apply to single stage, overhung, inline-style pumps that have horizontally mounted rotating assemblies and unique specialty purpose motors not larger than 5 horsepower.[47] The RTF designed the measures to be applied mid-stream, with the incentive applied at the manufacturer representative or distributor level. The measure identifiers that were established reflect this in their ability to be determined at or before point of sale. Each measure identifier is matched to a characteristic or attribute that could be objectively determined at the point of sale. Table 64 shows each measure identifier, along with the possible values for the identifier and the basis for each measure category.

Table 64: Summary of Circulator Measure Identifiers

Measure Identifier	Measure Categories	Objective Determinant
Sector	Residential	≤1/16 Nominal Motor HP
	Commercial	>1/16 Nominal Motor HP
Pumping Application	Hydronic Heating	Cast iron pump body
	Domestic Hot Water Recirculation	Bronze/stainless steel pump body with run-hours controls
	Unknown	Bronze/stainless steel pump body without run-hours controls
Nominal Motor HP	13 buckets ranging	Nameplate motors HP or max watts

[45] A Consensus recommendation was made regarding the test procedure in September of 2016 and a second consensus recommendation was made regarding the standard level in December of 2016.

[46] "HYDRAULIC INSTITUTE PROGRAM GUIDELINE FOR CIRCULATOR PUMP ENERGY RATING PROGRAM (HI 41.5-2018)." Available at: https://estore.pumps.org/Hydraulic-Institute-Program-Guideline-for-Circulator-Pump-Energy-Rating-Program-HI-415-2018-P2950.aspx

[47] This definition is consistent with the definition established by DOE's Circulators Working Group.

Measure Identifier	Measure Categories	Objective Determinant
	from 1/40 to 5 HP	
Efficiency Indicators	Pump Timer Controls	Presence of On-demand, Aquastat, or Learning controls at point of sale – *for DHW pumps only*
	Pump Speed Controls or PEI, if available	PEI or presence of differential pressure control, adaptive pressure control, differential temperature control, at point of sale – *for HH pumps only*

Sector: The sector of the pump can be residential or commercial. This identifier is not necessarily known when the distributor purchases the pump, so the subcommittee determined that any pump with a nominal motor HP greater than 1/16 horsepower is a commercial Circulator, and Circulators with a nominal motor horsepower of 1/16 or less is residential.

Pump Material: The metal of the pump is an identifier to determine the application of the pump. The RTF measures assume that the use of cast iron pumps is unique to the Hydronic Heating application. This assumption is based off the fact that hydronic heating systems are more contained and operate as closed loops, which decreases the relative corrosiveness of the water and allows for the use of cheaper, less corrosive resistant metals[48] (like cast iron) in these systems. In a domestic hot water recirculation system fresh water is constantly introduced.

The continual addition of fresh water to domestic hot water systems increases the dissolved oxygen content of that system, which increases the corrosiveness of the water.[49] This led the subcommittee to determine that all pump sold in the DHW application would be bronze or stainless steel. However, not all bronze or stainless-steel pumps are used in the DHW application. The subcommittee estimated that 45% of bronze/stainless steel pumps are sold into applications that are not DHW, such as ground source heat pumps or solar glycol loops, that have annual operating hours consistent with hydronic heating.

Nominal Motor Horsepower: The nominal motor horsepower defines the size of the circulator. Some circulators use motor horsepower to define the circulator size while other circulators are described based on their max Watts. There is ambiguity in the relationship between motor horsepower and max watts, so the measure development team established nominal motor horsepower as a consistent descriptor of circulator size. The RTF created ranges of circulator rated horsepower and max Watt that correspond to each nominal motor horsepower bin (based on DOE's performance database of circulators). Table 65 shows the nominal HP's that the RTF established, along with the rated HP Range and Rated Max Watt Range.

[48]Corrosion resistance determined by the specific materials position in the galvanic series. Bronze and Stainless Steel are more noble than Cast Iron (which mean they fall further down the galvanic series), therefore more resistant to corrosive attack.

[49]As water is heated, the amount of dissolved gasses the water can contain decreases. The dissolved oxygen then becomes entrained oxygen in the system, which when heated becomes more corrosive to metals increases amount of oxygen pitting seen in a system.

Table 65: Nominal HP Sizes with corresponding HP Range and Max Watt Rating

Nominal HP Size	Rated HP Range	Max W Range
1/40	≤1/30	≤50
1/25	>1/30 - ≤1/16	>50 - ≤100
1/12*	>1/16 - ≤1/8	>100 - ≤200
1/6	>1/8 - ≤1/6	>200 - ≤300
1/4*	>1/6 - ≤1/4	>300 - ≤400
1/2*	>1/4 - ≤1/2	>400 - ≤550
3/4*	>1/2 - ≤3/4	>550 - ≤750
1	>3/4 - ≤1.25	>750 - ≤1000
1.5*	>1.25 - ≤1.75	>1000 - ≤1300
2*	>1.75 - ≤2.5	>1300 - ≤1750
3*	>2.5 - ≤3.5	>1750 - ≤2350
4*	>3.5 - ≤4.5	>2350 - ≤3100
5*	>4.5 - ≤5	>3100 - ≤3700

* Not a DOE representative unit. Energy use was estimated by scaling 1 HP representative unit

Speed Control Mechanism or PEI/ER: For hydronic heating pumps, the speed control mechanism that is employed by the pump (or the pump PEI) is the main characteristic used to determine the efficiency of the pump, which is one of the main savings determinants. Table 66 lists the speed control methods.

Table 66: Speed Control Methods for Circulators

Speed Control Method	Description	PEI Range	ER Range
No Controls	The pump operates at the same operating point regardless of the demand on the system	1.00-0.86	Varies based on HP
Proportional Pressure Controls	A control (variable speed drive and integrated logic) that automatically adjusts the speed of the driver in response to pressure	0.85-0.76	
Adaptive Pressure Control	A pressure control that a pressure control that continuously senses the head and flow requirements in the system in which it is installed and adjusts the control curve of the pump accordingly	0.75-0.60	

Speed Control Method	Description	PEI Range	ER Range
Temperature-based Control	A control (variable speed drive and integrated logic) that automatically adjusts the speed of the driver continuously over the driver operating speed range in response to temperature.	<0.60	

Each speed control method aligns with a specific Efficiency Level (EL). While the EL is not used as a measure identifier, it is used in the development of the pump input power estimates for Circulators (discussed more in-depth in Section 5.1.1).

- No Controls (EL0, EL1, and EL2[50]) – The pump operates at the same operating point regardless of the demand on the system
- Proportional Pressure Controls (EL3) – incremental reduction in head by reducing flow to a control curve[51]
- Adaptive pressure controls (EL3.5) – The pump adjusts performance to meet a set pressure in the system.
- Differential Temperature Controls (EL4) – The pump adjusts the flow rate through the system to meet a target temperature differential

DOE's working group defined these efficiency levels, apart from adaptive pressure, which is based on information from the measure development team. All these speed control methods assume an Electronically Commuted Motor (ECM) is driving the pump.

The PEI and ER are an optional identifier of the pump efficiency for pumps rated based on the Hydraulic Institute's ER system. As PEI is not a statutory requirement, not all pumps have to participate in this voluntary program. To accommodate both pumps that were rated under the HI rating scheme and those that were not, the RTF measures were defined with two methods of defining efficiency: (1) a prescriptive approach based on the specific attributes of the control technology with which the circulator is shipped and (2) a performance-based metric approach based on the PEI or ER of the listed pump.

Timer Control mechanism: Timer controls are only applicable to Domestic Hot Water Recirculation (DHW) pumps and play a major role in determining the run hours of the pump in those applications. The drastic reductions in runtime of pumps associated with the different run-hours control types provide the opportunity for a significant reduction in energy saved from both pumping and water heating. The run-hours control mechanisms include:

- 24/7 Operation – Domestic Hot Water is recirculated through the system constantly

[51] The research also collected data from pumps using "Constant Pressure" speed control, which establishes a constant pressure line that the pump varies its speed to maintain. This control strategy is not captured in the EL in the Measures, but is different enough that the research team felt it merited its own EL, EL2.5.

[51] The research also collected data from pumps using "Constant Pressure" speed control, which establishes a constant pressure line that the pump varies its speed to maintain. This control strategy is not captured in the EL in the Measures, but is different enough that the research team felt it merited its own EL, EL2.5.

- On-Demand – The pump turns on by sensing the presence of a user, either through a button, sense of flow, motion sensor, etc.
- Aquastat – The pump operation (flow) maintains the temperature of the water in the loop at a specific level.
- Learning – The pump monitors when and how people use the system and only operates during those times.

The RTF developed 104 individual UES and incremental cost estimates based on these identifiers, across the commercial and residential sectors for both hydronic heating and domestic hot water recirculation applications. Increases in the efficiency of the pump and decreases in operating energy consumption dominate the energy savings for hydronic heating systems. Domestic hot water recirculation systems incorporate not just the energy of the pump into the energy savings estimate, but also the energy savings from decreasing the amount of water that is heated and the associated energy impact on the building HVAC system to compensate for changes in the amount of energy lost in the hot water loop. The RTF took these non-pump energy savings into account when developing the Energy Savings Model.

5.1.1 Energy Savings Model

The energy savings model developed for circulators by the RTF is based on the same high-level pump energy consumption equation used to develop the Clean Water Pump savings model, but also incorporates the energy from heating the water and the HVAC energy used to offset heat lost to the building. The equation for energy savings is

$$Energy_{SavingsCIRC} = \left(Energy_{BaseCaseCIRC} - Energy_{EffCaseCIRC}\right) + \Delta WHEnergy + \Delta HVACEnergy \qquad (20)$$

where

$Energy_{SavingsCIRC}$	=	Circulator energy savings
$Energy_{BaseCaseCIRC}$	=	Baseline energy consumption of the circulator
$Energy_{EffCaseCIRC}$	=	Efficient case energy consumption of the circulator
$\Delta WHEnergy$	=	Water heater energy savings associated with decreased pipe losses
$\Delta HVACEnergy$	=	HVAC energy savings associated with decreased pipe losses

The water heater energy savings and HVAC energy savings are only applicable to domestic hot water applications.

The model calculates baseline energy consumption as

$$Energy_{BaseCaseCIRC} = Hours_{BaseCase} * PER_{i,baseline} \qquad (21)$$

where

$PER_{i,BaseCase}$	=	Baseline weighted average input power of the circulator
$Hours_{BaseCase}$	=	Baseline operating hours of the circulator
i	=	Nominal HP

As discussed in Section 2.1, the RTF used DOE's PER to describe the weighted average input power of pumps at different efficiency levels (characterized by different control options). The PER of each efficiency level (PER_{EL}) is based on the representative units and PER established in DOE's Engineering Analysis, as well as the circulator test procedure established by the Working Group. DOE's Circulator Working Group established a specific test procedure and efficiency metric (PEI_{Circ}) for circulators that measures the weighted average input power of the tested circulator over a typical load profile. Since DOE did not finalize the test procedure, the Hydraulic Institute stepped in and developed a rating procedure, HI 40.7, that describes how to calculate both the PEI_{circ} and ER for circulator pumps. HI 40.7 is based on the recommendations of DOE's Circulator Working Group. Baseline PER is the weighted average PER for all efficiency levels, for a circulator in a specific motor horsepower range.

The baseline operating hours for circulators is determined differently for each application. Operating hours, for the hydronic heating application, is determined by the pump's installation sector. Table 67 shows the baseline operating hours for hydronic heating in each sector

Table 67: Baseline Operating Hours, Hydronic Heating

	Residential	Commercial
Operating Hours	2,605	2,916

For domestic hot water recirculation systems, the baseline operating hours is a sector-specific average of the operating hours for each run-hours-control method, weighted by the prevalence of those controls in the market. The baseline also accounts for differences in controls between existing and new construction. The average of each control strategy (weighted by the fraction of consumers estimated to use them) is used as the existing construction operating hours, and on-demand operation hours are used as the new construction estimate (because code requires on-demand control in all new construction). The estimated baseline operating hours is then calculated as a weighted average of the existing and new construction estimates, assuming 95% of the market is existing constructions and 5% is new construction.

Table 68: Baseline Operating Hours, Domestic Hot Water recirculation

Control Variety	Residential	Commercial	Fraction of Consumers
	Operating Hours		
No Control	8760	8760	50%
Timer	7300	6570	25%
Aquastat	1095	1095	20%
On-Demand	61	122	5%
Learning	1095	1095	-
Existing Construction	6427	6248	95%
New Construction	61	122	5%
Baseline Op Hours	**6109**	**5941**	**-**

The model calculates efficient case energy consumption as

$$Energy_{EffCaseCIRC} = Hours_{EffCase} * PER_{i,Eff} * AdjFactor \quad (22)$$

where

$Energy_{EffCaseCIRC}$	=	Efficient case energy consumption of the circulator
$Hours_{EffCase}$	=	Efficient case operating hours of the circulator
$PER_{i,Eff}$	=	Efficient weighted average input power of the circulator
$AdjFactor$	=	Factor that compensates for motor oversizing and single- and multi-zone energy consumption differences
i	=	Nominal HP

$PER_{i,Eff}$ is the weighted average input power for a pump's specific efficiency level, based on the pump's available speed control method. The measure development team created efficiency level- specific PER's using DOE's Working Group's analysis.

The operating hours for the efficient case are control specific. For hydronic heating the operating hours are based on either constant speed or variable speed control. The operating hours for domestic hot water are specific to each sector and control type (listed in Table 68). The Adjustment Factor compensates for the differences in energy consumption between single and multi-zone hydronic heating systems and over sizing. It adjusts the weighted average input power (which is based on DOE's analysis) to the expected real-world energy consumption of the circulator, as installed in the field.

Water heater energy savings includes both electric energy savings, in kWh, and savings of gas, in therms. The UES measures estimate water heater energy using information from previous research and engineering judgement of the RTF research team, weighted for the type of water heating equipment used. The HVAC energy savings accounts for the decrease in heat that radiates into the space through the pipe walls. The model calculates HVAC energy savings as a percent of water heating savings.

5.1.2 Assumptions and Research Questions

The RTF and measure development team used the best available data to construct these measures, but there were assumptions and engineering judgements made during the process. Similar to Clean Water Pumps, the RTF developed a research plan to investigate the key variables underlying the energy savings estimates.[52] The RTF's Research Plan states that Circulator inputs and assumptions fall into two general categories:

- **Pump and controls operational characteristics** include variables such as pump material, available speed controls or run-hours controls, nominal shaft horsepower, pump efficiency, operating characteristics of the different control strategies, and pump system characteristics.
- **Installation and market characteristics** include variables such as the current practice efficiency mix of circulators, the market breakdown of circulator shipments in the region by material and application, the control strategy selected by installers, and control strategy retention.

The RTF's Circulator research plan lays out eight key research questions for Circulators. The research questions related to installation and market characteristics include:

- ***Current practice efficiency level.*** Two items are needed for this measure's baseline:

[52] https://nwcouncil.app.box.com/s/u85zfgqij1bt5ail3gveqi83ebxnylhk

- Mix of circulator pump efficiency levels (EL0-EL4; see Appendix A) reflected in the market (typical choices of eligible end-users);
  - Fraction of new pumps that are installed in new buildings or other circumstances where a code requirement specifies efficiency beyond the minimum standard.
- ***System type mix by pump material type and horsepower.*** The RTF expects that nearly all cast iron pumps are installed in hydronic heating systems. However, some cast iron pumps may be installed in cooling systems or other applications. In addition, brass/stainless pumps are installed in an unknown mix of system types.
- ***Installed control strategy mix by available circulator speed controls.*** Circulator pumps that are equipped with advanced speed controls typically allow the installer multiple control type options. The options that installers typically select are not well understood.
- ***Control strategy retention.*** In some applications, especially DHW recirculation in MF buildings, some efficient control options are likely to increase end-user wait times relative to un-controlled (8760) recirculation. The fraction of cases where controls are deactivated soon after installation is not known.

The research questions related to pump and controls operational characteristics include:

- ***Operating Hours.*** Operating hours need to be empirically measured under various baseline and efficient-case control types.
- ***Average Power***. Average power (kW) needs to be empirically measured under various baseline and efficient-case control types.
- ***Water heating energy savings.*** Water heating energy savings need to be empirically measured or reliably modeled for different efficient-case run-hour control types.
- ***HVAC interaction factor.*** RTF expects to use data collected in the course of this research (e.g., the fraction of DWH recirculation piping found in conditioned spaces) to improve engineering estimates of HVAC interactions.

The research in this report was performed to investigate the research questions related to the operation of pumps in the stock and was not designed to answer the research questions that pertain to the market distribution or baseline characteristics. Specifically, the research team addressed specific assumptions made in the development of the measures in four key areas, discussed in this Section. In addition, the research team analyzed the collected data to understand energy savings from the different control strategies and collected anecdotal information, as it was available, on the common control strategies found in the field.

This research did not collect information related to market inputs due to the vastly different research strategy and approach necessary to evaluate those inputs. As described in more detail below, this research focused on gathering data on pump operation and installation characteristics via existing and primary data collection in the field, similar to the approach for Clean Water Pumps. The research did not include a shipments data analysis or market research component. NEEA is currently fielding a market research project which hopefully will provide additional insight into the market research related questions.

Additionally, the research did not pursue validating the assumptions related to HVAC interaction, since that would also require additional data collection of building characteristics and HVAC energy consumption that was beyond the scope of the current study. NEEA's new Commercial Building Stock Assessment may contain relevant information for answering this research question.

5.1.2.1 Operating Hours

The RTF measures assume hydronic heating operating hours are dependent on the pump's speed control and sector. Table 69 shows the estimated operating hours for hydronic heating systems and Table 70 shows the estimated annual operating hours for domestic hot water recirculation systems. Domestic hot water recirculation systems assume operating hours are dependent on the run-hours control strategy and sector of the pump.

Table 69: RTF UES Measure Hydronic Heating Operating Hours

Sector	Constant speed	Variable speed
Residential	2,605	2,768
Commercial	2,916	3,148

Table 70: RTF UES Measure DHW Operating Hours

Control Variety	Operating Hours				
	Baseline	No-Control	Aquastat	On-Demand	Learning
Residential	6,109	8,760	1,095	61	1,095
Commercial	5,941	8,760	1,095	122	1,095
Market Share	NA	50%	25%	20%	5%

The hydronic heating operating hours estimate is informed by a study performed by EPRI and information from DOE's Circulator Working Group analysis. The baseline for hydronic heating assumes a constant speed pump. The operating hours associated with the different control methods for domestic hot water recirculation are based on DOE's Working Group Analysis and previous research reports[53]. The rationale for each control strategy's operating hours is as follows:

- **No Control:** Constant operation for a full year
- **Aquastat:** 3 hours per day
- **On-Demand:** 10 minutes per day residential, 20 minutes per day commercial
- **Learning:** assumed to be the same as Aquastat

As discussed in Section 5.1.1 the baseline operating hours for domestic hot water recirculation is the weighted average of the operating hours for each control method. This research collected operating information on circulators with these control strategies and calculated the observed operating hours for

[53] The previous research reports used to inform the operating hours research are listed in the RTF Measure Workbook on Tab 'OpHours', available at: https://rtf.nwcouncil.org/measure/circulator-pumps

each control strategy. The research team designed the research to sample each control strategy equally and will not be analyzing the market share each control strategy occupies.[54]

5.1.2.2 Pump Energy Input

Pump energy input is based on the PER of the pump. For the baseline, PER_{base} is an average of all the PER_{EL}, weighted by the efficiency level market distribution. The PER_{Eff} is the PER_{EL} designated for each specific speed control type. This research will investigate the average power, measured under various control cases, but will not investigate the market distribution of control types or selected settings based on the control types available.[55]

5.1.2.3 Water Heater Energy Savings

The water heater energy savings are only applicable to the domestic hot water application and represent the largest portion of the energy saving for that application. The collection of loop supply and return temperature information will inform the investigation of loop losses associated with each control strategy.

5.1.2.4 Anecdotal Response to Advanced Control Strategies

The control strategies that are available on the Circulator are used to determine the Efficiency Level, however, the availability of advanced controls does not indicate that the control strategies are employed. Where available the research team compiled anecdotal information on the reception of the different control strategies and recidivism to less advanced control methods.

5.2 Data Collection Methodology

The data collection and management for Circulators was much the same as for the Clean Water Pumps, presented in Section 4. As the energy savings model is slightly different for circulators (it also includes water heater and HVAC energy savings), the circulator data collection includes slightly different data points, but the method of leveraging both existing data and primary data collection remains the same. The team collected both audit data and operational data for each pump, with the definitions of these data consistent with the definitions laid out in Section 4.2.

5.2.1 Data Sources

While the research collected both existing data and primary data to describe circulator pumps, one of the key questions of the research aimed to investigate the differences in energy usage across different control strategies on the same system. This, along with a lack of existing data available, made it a necessity to increase the percentage of the sample filled through primary data collection.

5.2.1.1 Existing Data

There were two sources of existing data for Circulator pumps: (1) previously logged data from building owners/operators and (2) existing literature and studies.

The research team also attempted to collect existing data in the same method as Clean Water Pumps, leveraging Building Management Systems and Control Systems to collect data from pumps connected to automation systems. However, through the data outreach the research team discovered most Circulators

[54] As noted previously, NEEA's concurrent Market Research Study or Commercial Building Stock Assessment may contain relevant data for understanding the market or stock distribution of circulator control strategies.

[55] Again, NEEA's Commercial Building Stock Assessment may be a good source of information for understanding the market or stock distribution of circulator control strategies.

are not connected to control systems. In discussion with building operators and facilities staff it became evident that Circulators are such a small piece of equipment most facilities simply install them, turn them on, and don't bother to connect them to the building's BAS. Connecting the pump to the control system can be more expensive than the cost of the Circulator. These barriers led to the research team collecting very few pumps through BAS's or previously installed monitoring systems.

Despite the lack of existing monitoring information from building owners and operators, there is a reasonable amount of information currently available that directly investigates the efficacy of different circulator control strategies. On-demand control for pumps on domestic hot water systems is a requirement of the Energy Code in a large portion of the country,[56] which has spurned research into the benefits and energy savings of that control strategy. The majority of the existing research, which is discussed more thoroughly in Section 5.3, focuses on on-demand control, but the research team was able to reach out to researchers and incorporate data collected for previous research into this analysis for multiple different controls strategies.

5.2.1.2 Primary Data

Primary Data collection for Circulators took two different forms. The first method remained consistent with the Clean Water Pump research and involved installing metering on pumps found in the field. The second method involved the installation of new pumps along with monitoring equipment on some systems. This allowed the research team to toggle between control methods on the same pump and investigate the energy savings associated with different control strategies on the same systems. This second method was particularly important in investigating the operation of more advanced control systems, which are not commonly found in the existing stock.

5.2.2 Sample Strata

The RTF Research Strategy for Circulator Pumps[57] proposed a sample frame for circulator data collection based on the sector and control strategy of interest, as shown in Table 71. The research team adapted it during the course of data collection to better reflect the realities of circulator pump and control availability and applicability within each sector, as described in detail in the subsequent section.

Table 71: RTF Circulator Sample Targets

Sector	Hydronic Heating				Domestic Hot Water			
	SS*	P**	AP***	Temp.	24/7†	AP	Learning	OD‡
Single Family	5	5	5	5	5	5	5	5
Multi-Family	5	5	5	5	5	5	5	5
Commercial	5	5	5	5	5	5	5	5

* Single Speed
** Proportional Pressure
*** Adaptive Pressure
† 24/7 Operation
‡ On-Demand

[56] The International Energy Code, available at https://codes.iccsafe.org/, required the application of on-demand controls in 2012.
[57] The RTF Research Strategy for Circulator Pumps can be found at https://rtf.nwcouncil.org/measure/circulator-pumps

5.2.3 Data Collection Outcomes

The research team has to refine the sample frame targets for circulators significantly over the course of the research study due to challenges in recruitment and the applicability of some control strategies to different sectors. In addition, similar to Clean Water Pumps, the research team modified the definitions of some sample strata to better reflect available equipment and applicable control strategies for different sectors. The final circulators sample disposition is shown in Table 72.

Table 72: Final Sample Frame Sample Disposition

Sector	Hydronic Heating				Domestic Hot Water			
	SS	P	AP	Temp	24/7	AP**	Learning	OD/AQ
Single Family	10	5*	4	2	5	2	1	6
Multi-Family	0	0	0	0	24	13	0	5***
Commercial	3		N/A		27		2	7

*The proportional pressure section of this sample frame for Hydronic Heating includes 2 proportional pressure pumps and 3 constant pressure pumps.
**AP in Domestic Hot Water also includes Timer Controls
***On-demand controls implemented in multi-family and commercial sites are Aquastat-style controls that maintain loop temperatures at a fixed temperature.

5.2.3.1.1 Hydronic Heating

The study was able to collect data on 24 different control strategies from 10 different sites on residential hydronic heating pumps from a combination of existing and primary data sources. All of the hydronic heating data were collected through primary data collection. Of the 10 sites, 4 were homes that included new pump retrofits that enabled the research team to test multiple control strategies.

However, despite persistent recruitment, the research team was not able to identify any existing data or new sites for the multi-family hydronic heating sample strata. This is partially due to the low penetration of hydronic heating systems in multi-family buildings in the Pacific Northwest. Specifically, the 2016 Residential Building Stock Assessment estimates that 1% of multi-family buildings have hydronic heating systems (NEEA 2018). Another challenge was the timing of data collection and how it coincided with the heating season. Although recruitment on all sample strata occurred throughout the 2018/2019 winter season, several sites that had originally agreed to participate dropped out in the early spring and it was not possible to replace the sites on such short notice. This is a gap in the current research and should be pursued more in future research in multi-family circulator energy savings are of interest to the Region.

Similarly, the research team identified very few circulators in hydronic heating applications in the commercial sector. As was the inverse case with Domestic Hot Water Recirculation Clean Water Pumps observed in section 4.2.3.2.5, most of the hydronic heating pumps in commercial buildings are nominal horsepower Clean Water Pumps, not circulators. As such, the research team eliminated this sector from the research sample frame. The team had already collected data on 3 single-speed circulator pumps in the commercial sector and included a high-level analysis of these pumps, but did not recruit additional sites.

5.2.3.1.2 Domestic Hot Water

Domestic hot water recirculation pumps were more challenging to identify in single-family homes, as recirculation systems are not that common. However, the team was able to collect data from 1 existing data site and 5 primary data collection sites. Of the 5 primary data collection sites and the 1 existing site, 3 featured sites with new pumps where the controls where flip-flopped throughout the monitoring period. The main changes made to the single-family DHW sample frame were reducing the sample targets for the adaptive pressure and on-demand control strategies due to limitations of the control strategies available on the various residential circulator models.

First, many of the more efficient control types are newer control strategies and are not yet common in the market. Also, different circulator manufacturers offer different circulator models with different control options and no manufacturer offers a circulator with all of the different control strategies the study was looking to test. For example, only three manufacturers offer models that are "On-Demand", as defined by the RTF measures (the recirculation pump is started based on receiving a signal from the action of a user of a fixture or appliance and cannot initiate water circulation based on other inputs, such as water temperature or a preset schedule). For these pump models, "On-Demand" is the only efficient control strategy available; other control modes, such as aquastat or timer control, are not also available on these pumps. Finally, not all circulators are direct replacements for the existing pump installed at a given site, meaning that in some cases the choice of pump retrofit and available controls was dictated based on the dimensions of the pre-existing equipment. Retrofitting on-demand pumps can also be complicated as new remote sensors need to be installed at fixtures and occupants need to be trained on their use.

To account for these barriers, for each site, the research team attempted to test as many control strategies as possible, based on the dimensions of the existing equipment, the flexibility of the occupants, and availability of different control strategies on the new retrofit pump.

For the multi-family and commercial sectors, recirculation loops are much more common. However, it was very uncommon to find pumps with advanced control options; almost all pumps identified for primary data collection operated 24/7. To collect data on more efficient run-hours control options, the research team retrofit pumps at some sites. However, the team encountered the same challenge regarding availability of pumps controls and the retrofit ability of different pump models. That is, for the retrofit pumps with advanced run hour control options, the efficient case pump was often dictated based on the dimensions of the previously installed pump and the available control options where dictated by what was on that pump. Again, not all options were available on all pumps. For this reason, the Adaptive Pressure control strategy sample target was combined for multi-family and commercial, since this control strategy is likely to operate similarly in both multi-family and commercial applications.[58] In addition, only one pump model sized for the commercial sector was equipped with learning-based controls, which limited the number of sites where that control strategy could be evaluated.

Multi-family and commercial sites had the additional challenge related to control applicability. That is, commercial and multi-family buildings feature large recirculation loops that need to stay hot to ensure reliable hot water delivery to occupants within reasonable time frames. Run hours control strategies, like

---

[58] The adaptive pressure control strategy is a speed control strategy that works by automatically reducing the speed of the pump to reduce flow and more appropriately match the operating requirements of the system (i.e., overcome oversizing). Since both multi-family and commercial recirculation loops are commonly single-zone systems and sizing characteristics are likely to be the same, the research team anticipates the operation of adaptive pressure in these systems will be similar.

on-demand, that allow the recirculation loop to cool down below acceptable temperatures are not advised in these applications and were not pursued due to concerns with occupant satisfaction. Most manufacturers of on-demand controls, when adapting them to commercial and multi-family buildings, install low temperature dependencies or schedule-based operation that disqualifies them from being considered "on-demand" controls based on the RTF definition. Based on discussions with manufacturers and building designers, most new buildings are installing these temperature- or schedule-based control strategies to comply with the requirements for "on-demand" recirculation control in new building codes. These temperature-based controls are implemented two different ways: (1) with a single-speed pump that turns the pump on and off based on fixed cut-in and cut-out temperatures or (2) with a variable speed pump that reduced the speed and flow of the pump based on the return water temperature (or temperature at the furthest fixture) in order to maintain a given temperature at the end of the loop (or furthest fixture). In the subsequent research findings, these are referred to a "Aquastat" and "Temperature-based speed control," respectively (see section 5.4.1 for more information). The RTF measures only established savings for DHW circulators equipped with on-demand controls or Aquastat controls.

5.2.4 Data Standardization and Annualization

As with Clean Water Pumps, the research needed a robust method for standardizing data collected in the field (collected for various purposes and over varying timeframes) and annualizing that data to represent Circulator operation over the course of a year. This similarity allowed the research team to leverage the framework established for Clean Water Pumps and adjust it for differences in the type of data collected for Circulators. This section reviews changes to the Clean Water Pumps Data Standardization and Annualization process required to manage the collection, processing, and annualization of Circulators.

5.2.4.1 Audit Data Collection and QAQC Process

The Data Submission Form used to collect Audit Data for Clean Water Pumps was also used to collect Audit Data for Circulators. The same Data Contributor Information was collected for both Clean Water Pumps and Circulators, but the Required Pump Information and Optional Pump information differed. Table 73 lists the Audit information that was collected and the purpose for collection. The Data Submission Form provides a detailed list of the audit data points collected.

Table 73: Audit Information and purpose for collection, Circulators

Audit Information	Justification/Purpose
	Required Circulator Information
Pump Nameplate Information	To determine pump power input, pump class, motor oversizing, pump metallurgy
Motor Nameplate Information	To determine PEI for unrated pumps and understand motor oversizing
Application	To determine variability in operating hours and pump power consumption based on application
Pump Control	To research the variation in pump power, energy consumption, and operating hours based on control strategy
	Optional Circulator Information
Operation of Pump Controls Over Time	To research control method recidivism within different sectors.

As data contributors started submitted audit and operational data for circulators the analysis team realized that most times manufacturers do not develop a pump curve document with the pump efficiency for circulators. Most often they publish a pump curve with Head as a function of flow rate but leave off power or efficiency. This gap in published data affected the majority of Circulators collected and made it impossible to determine the operating points needed to calculate the PEI or ER for submitted circulator pumps.

The same QAQC Process established for Clean Water Pumps was also used for Circulators. An audit data QAQC Checklist was used, along with "discrete answer cells" within the Data Submission Form to standardize the submitted data.

5.2.4.2 Operational Data Collection and QAQC Process

The operational data submittal and QAQC process for Circulators followed a similar framework as Clean Water Pumps. The database has three separate operational data tables, one to store the submitted raw data, one to store the submitted data standardized to a 1-hour timestamp, and a final table storing the annualized values.

The Circulator research answers different research questions than the Clean Water Pumps research, which necessitated collecting different operational variables. Specifically, this research investigated the water heater energy savings associated with different circulator control strategies, which required the research team to collect operational information on the return and supply temperature for domestic hot water recirculation applications. "Supply water temperature" refers to the temperature of the water directly after the water heater[59] and the "Return water temperature" is the temperature of the water after is has been circulated through the entire loop and is about to be reheated by the water heater. These values were standardized to degrees Fahrenheit (F) in the standardized table.

5.2.4.3 Data Annualization Process

The process used to annualization the Clean Water Pump operational data was used as the outline for the Circulator annualization. As with Clean Water Pumps the annualization approach varied based on the pump application and known or expected dependencies.

For hydronic heating applications the annualization model was the same model as the Commercial Clean Water model. Hydronic Heating Circulators and Heating Clean Water Pumps are performing the same service with the same input-to-result (a change in temperature/user input changes the flow of the pump to meet a setpoint). The difference between the two is the size of the system; Clean Water Pumps are installed on large recirculating heating systems whereas Circulators are installed on smaller systems.

The model has been augmented for domestic hot water recirculation pumps because of the incorporation of supply and return temperature. We did not alter the process for predicting state, flow, and power.

[59] The supply temperature is not necessarily equivalent to the Water Heater Temperature. When the recirculation pump is operating the supply temperature will be at or very near the Water Heater temperature, but when the pump is off the supply temperature will slowly cool down to the ambient air temperature.

For the supply and return temperatures, we generally model the supply temperature using the same model structure and inputs as we do for modeling the flow when the pump is on. We then use existing operations data to identify the proportional relationship between ΔT (The difference between supply and return temperatures) and flow,[60] as shown in the following equations:

$$\hat{k} = median\left(\frac{\Delta T_t}{f_t}\right) \tag{23}$$

$$\hat{R}_t = \widehat{S_t} - \hat{k}(\hat{f}_t) \tag{24}$$

Where $\hat{k}$ is the constant of proportionality, $\widehat{S_t}$ is the predicted supply temperature at time t, $\widehat{R_t}$ is the predicted return temperature at time *t*, and $\widehat{f_t}$ is the predicted flow at time *t*. The process described for generating predictions of supply and return temperatures represent the predictions only when the circulator state is on.

When the circulator is off, both temperatures will cool toward a calculated surround temperature. The supply and return temperatures each use a different surround temperature, but for both, it is the minimum temperature observed in the standardized data. The amount of cooling during the off states is determined by calculating a cooling constant ($\hat{c}$).

$$\hat{c} = median\left(\frac{T_{t-1} - T_s}{T_t - T_s}\right) \tag{25}$$

$$\hat{T}_t = T_s + \hat{c}(\hat{T}_{t-1} - T_s) \tag{26}$$

Where T_t is supply temperature or return temperature at a given time and T_s is the associated surrounding temperature.

In the case where only supply and return temperatures are known and the flow and power are not known, then we model the supply temperature and the temperature difference using our linear LASSO regression method described above.

5.3 Review of Existing Literature

5.3.1 Domestic Hot Water Recirculation

The three different energy savings mechanisms associated with domestic hot water recirculation (pump energy consumption, water heater energy consumption, and HVAC system compensation) and the requirement in some geographies that hot water recirculation systems have on-demand controls (IECC 2015) have created a body of information on the operation of domestic hot water recirculation pumps

5.3.1.1 Single Family Domestic Hot Water Recirculation

Gary Klein and Associates performed research on the energy consumption of recirculation systems, with a focus on the different energy consumption due to changes in control method (Klein and Acker 2006). The research was performed on one house in Central California. The research used the same plumbing layout to monitor the different energy consumption of four pump control strategies: continuous circulation, Aquastat (or temperature controlled), intermittent pulsed timer, on-demand control, and learning. The research concluded that the annual energy savings due to on-demand controls is dependent on the number of hot water use points and can range from 200 – 400 kWh/year. This study also determined that

[60] when flow is unknown and power is known, we find the proportional relationship between ΔT and power based on the $\sqrt[3]{power}$.

the on-demand pumping system operated 1 minute for every gallon of water used and the timer-controlled system operated for 16 hours per day.

Energy Solutions, in partnership with Grundfos and PG&E performed research on domestic hot water recirculation pumps in California (Grundfos 2017). The focus of this study was to determine the hours of operation of a domestic hot water pump using various control strategies and the instantaneous energy consumption of the pump. They monitored 13 pumps using 4 different control methods: constant operation, timer control, Aquastat (or temperature control) and timer + Aquastat control. The annual operating hours that were observed for constant operation were, as one would assume, 8760 hours per year. The operating hours observed for Timer operation were 6891 hours per year (between 9 and 24 hours per day) and the operating hours for Timer + Aquastat were 4,380 hours per year (12 hours per day). This study did not report the operating hours for Aquastat control. The pump power draw was observed for steady state operation, as well as for instantaneous demand and sustained demand draw. It was observed that the average power demand of the pump at steady state operation was 26.7 watts, whereas the instantaneous demand draw was on average 10.7% less, and the sustained demand draw was on average 6.9% less.

Metlund Hot water DMAND (ACT D'MAND) Systems were installed in 5 homes in Palo Alto, California (Ally, Tomlinson and Ward 2002). Oak Ridge National Lab (ORNL)completed the research and aimed at estimating the water savings associated with on-demand control, with a secondary task of quantifying the energy savings from decreasing water usage. The annual operating hours of the on-demand-controlled pump varied from 9.05 hours/year to 38.5 hours per year. The research presented the water and electric savings as values per point of use (faucet). For a household of four the water savings varied from 900 gallons to 3000 gallons per point of use per year and the electric savings varied from 200kWh to 400kWh per year. This study notes that it relied on the use of a floating reference temperature for the energy savings calculations (the temperature of the supply water is assumed to be the ambient temperature of the basement), and the data acquisition should be adjusted to enable direct measurements of process variables.

Table 74 summarizes the energy and water savings presented in the literature.

Table 74: Single Family Domestic Hot Water Literature Summary

Organization	Buildings Type	Control Method	Operating Hours	Energy Savings (pump and water heater)
Gary Klein and Associates	Single Family	On-demand	1 minute/gallon used	200-400kWh/year
		Timer Control	16 hours/day	
Energy Solutions	Single Family	Aquastat control	4,380	6.9%-10.7%
		Timer Control	6,891 hours/year	
ORNL	Single Family	On-Demand	9-38.5 Hours/year	30%

5.3.1.2 Multifamily Domestic Hot Water Recirculation

The energy code requiring on-demand controls on Commercial and Multifamily DHW recirculation loops has instigated research on the energy savings associated with this control strategy.

The Levy Partnership performed research on 4 different sites in New York City in 2013 and 2014 (Dentz, Jordan; Ansanelli, Eric; Varshney, Kapil PhD, PE 2015) to evaluate the energy savings associated with different control methods for domestic hot water recirculation systems: fixed speed temperature-based on-demand control, temperature modulation control, and fixed speed temperature-based on-demand + temperature modulation control. The research showed that the for fixed speed temperature based on-demand control the water heater energy consumption was decreased by 9%, for temperature modulation the water heater energy consumption decreased by 4%, and for a combination of the two control methods the energy consumption of the water heater decreased by 14%. The annual operating hours seen by the implementation of fixed speed temperature-based on-demand control was, on average, 65.4 hours per year (with daily operating times ranging between 1-15 minutes). This report coupled the annual operating hours with the recirculation pump power draw and determined the annual pump energy savings ranged from 1,708 kWh/year to 2602 kWh/year.

A study performed by Heschong Mahone Group looked at the overall energy savings from recirculation controls. The study monitored 28 multifamily buildings in California (Zhang 2013) and tested 3 different control strategies: on-demand control (it is not specified whether this on-demand control method is temperature dependent), timer control, and temperature modulation. This study showed that 33% of the natural gas energy used in the domestic hot water system was lost to the recirculation system. Through testing the three different control strategies HMG saw an average of 11% energy savings from on-demand control, 1% energy savings from timer control, and 7% energy savings from temperature modulation.[61] For the timer-controlled systems the pump was set to run for 18 hours per day, or 6,570 hours per year. For on-demand control systems the monitored operating hours for these pumps was between 377-2,902 hours per year.

Enovative performed a case study in 2008 on the effectiveness of a "Demand Controller" in a Multifamily Building (Enovative 2008). The full case study is no longer available on Enovative's website (a summary sheet is available on-line) so the research team was unable to determine the definition of "Demand controller" used in this case study. The study monitored the operation of a DHW recirculation system in a 5-story multifamily building. The study concluded that the "demand controller" reduced the pump electricity use by 78% and decreased the water heating energy by 30%.

Table 75 summarizes the findings from these studies. The data collected by The Levy Partnership was incorporated into this research's Circulator data set.

[61] These energy savings refer to the total system energy savings (pump and water heater).

Table 75: Multifamily Domestic Hot Water Literature Summary

Organization	Buildings Type	Control Method	Pump Savings	Water Heater Savings
The Levy Partnership	Multifamily	FS-TB-Demand*	1,708-2,602 kWh/year	6-12%
		Temperature Modulation	NA	2-8%
		On-Demand + TM	1,708-2,602 kWh/year	12-15%
Heshong Mahone Group	Multifamily	On-Demand Control	Average of 11%	
		Timer Control	Average of 1%	
		Temperature Modulation	Average of 7%	
Enovative Case Study	Multifamily	Demand	78%	30%

*Fixed Speed Temperature-Based On-Demand

5.3.1.3 Commercial Domestic Hot Water Recirculation

The Minnesota Center for Energy and Environment (MN CEE) performed their own study on the effectiveness of on-demand controls in Commercial Buildings (Schoenbauer, Sweeney and Guada 2018). MN CEE researched different control strategies at 6 different facilities, spanning 3 different building types (hospitality, education, and office). This study looked at the energy savings that can be achieved from on-demand controls and the percentage reduction in runtime from continuous operation that on-demand controls produces. This research used a fixed speed temperature-based on-demand controller that activates the recirculation pump when "both (a) the recirculation loop return water has dropped below a prescribed temperature and (b) a DHW demand is sensed as water flow into the system" (Schoenbauer, Sweeney and Guada 2018). On average 87% of the pumping energy was saved and 13% of the energy to heat water was saved. The operating hours for on-demand controlled pumps ranged from 226-2,628 hours per year.

Timer controls for domestic hot water recirculation systems were tested in commercial buildings by Oracle America Inc (Khattar and Somani 2010). The field research measured a water heater energy savings of 27%. The timer controller was set to only run during occupied hours, with an operating hours reduction from 24 hours/day to 13.5 hours per day (the pump was not operated on the weekends). The timer controlled annual operating hours were 3,510 hours per year, down from 6,240 hours per year with constant recirculation.

The National Renewable Energy Laboratory (NREL) performed research on Domestic Hot Water recirculation systems in Commercial Buildings (Dean, Honnekeri and Barker 2018). This study investigated the energy savings associated with high performance, sensor-integrated pumps. The research logged pump operation for two domestic hot water recirculation pumps in a commercial office building in Colorado. The research controlled the pumps by establishing a return temperature setpoint that the system could not drop below. The pump varied recirculation flow to meet this temperature setpoint. This strategy is similar to the "variable-speed temperature-based on-demand" control defined above. This research concluded that the high-efficiency pump resulted in a decrease in pump energy usage of between 90% and 96%.

Table 76 summarizes the results from these studies. The research team incorporated the operational data collected for the study performed by NREL into this research.

Table 76: Commercial Domestic Hot Water Literature Summary

Organization	Buildings Type	Control Method	Pump Savings	Water Heater Savings
MN Center for Energy and Environment	Office	FS TB-Demand	88%	20.30%
	Hospitality	FS TB-Demand	70-93%	9.9-15.9%
	Education	FS TB-Demand	96.20%	11.40%
Oracle America, Inc	Commercial	Timer	43%*	27%
NREL	Commercial	Temperature (Efficient pump)	90%-96%	Not Quantified

*Fixed Speed Temperature-Based On-Demand

5.3.2 Hydronic Heating

There has not been a large amount of research within the single-family sector that looks at the energy use and run-time of pumps. Most of the research and reports that were reviewed looked more closely at the energy consumption of the water-heating equipment. The use of combination systems, where the heat source serves both the space heating and domestic hot water needs is a focus of the current research. This is potentially understandable due to the low penetration of hydronic heating. According to the US Census only 11% of homes use steam or hot water systems. Such systems are even less common in the Northwest, with NEEA's RBSA showing boiler-heating only present in 2.5% of single-family homes (NEEA 2018) and 1% of Multifamily buildings (NEEA 2018) in the Northwest. NEEA's CBSA shows 11% of the Northwest's commercial buildings heat with boilers (NEEA 2014).

5.3.2.1 Multifamily Hydronic Heating

The lack of research on hydronic heating pump energy consumption is highlighted in the Building America Expert Meeting Report of Hydronic Heating in Multifamily buildings (Dentz 2011). The goal of this meeting was to bring together experts in a field to refocus Building America's research priorities. This meeting focused on cost-effective controls and distribution retrofit options for hot water and steam space heating in multifamily buildings. The meeting is separated into 4 sections, and in 2 out of the 4 sections it was addressed that the pumping energy for hydronic heating systems hasn't been characterized well. Along with that, one of the main research gaps that was identified is the electricity costs for different hydronic heating strategies.

5.3.2.2 Single Family Hydronic Heating

The Consortium for Advanced Residential Buildings (CARB) did research the optimal components of a hydronic heating system that resulted in increased overall system efficiency (Arena and Faayke 2013). They also looked at the impact of variable speed pumps on energy use. The research monitored three houses, all with similar characteristics. This study monitored a total of nine pumps (3 in one house, 2 in the second house, and 4 in the third house). The research spanned 7 test periods from October through February. The results of this study were focused on the efficiency of the entire system and determined that a condensing, modulating boiler equipped with an on-demand DHW heat exchanger with thermostat setback controls and a high-efficiency pump is the most efficient combination of equipment for a hydronic heating system. Through monitoring these pumps they determined that installing a high efficiency pump that displays flow rate and energy consumption makes it easier to ensure design conditions are being met. This study measured average pump run-time at 1,241 hours over the course of 86 days.

5.4 Results and Discussions

This section reviews the key findings from this research related to operating hours, average input power, water heater energy savings, the energy savings of different control modes, and additional insights the research team gathered throughout the research.

5.4.1 Classification of Control strategies

In collecting data to fill the sample strata established by the RTF's Research Strategy the research team discovered that the control strategies established by the RTF did not fully capture the range and variation in control strategies distributed by manufacturers. This section presents the findings for both hydronic heating control strategies and domestic hot water control strategies.

5.4.1.1 Hydronic Heating

The RTF only developed energy savings measures for hydronic heating circulators that are based on varying the operating speed of the pump (referred to in this research as "speed control strategies"). Timer controls were not incorporated into the measure set (or research strategy) because a hydronic heating pumps operating state is controlled by the thermostat or water heating equipment's control logic. This assumption was corroborated by the pumps monitored during the research, as none were equipped with timer controls independent of the heating system.

The RTF's measure control strategies included differential pressure speed controls, differential temperature speed controls, adaptive pressure speed controls, and unknown speed controls. However, there are two distinct types of "differential pressure control" that are available in the field and have different energy consumption results: constant pressure control and proportional pressure control. Constant pressure control continually adjusts the operating speed of the pump to maintain the pressure in the system at a constant value, whereas proportional pressure adjusts the speed of the pump along a pre-established control curve that decreases the pressure as speed decreases. In addition, the team observed many pumps equipped with constant speed controls that were not addressed in the RTF work, which allow the user several discrete speed options that can be selected based on manual user input. The speed controls and their definitions are show in Table 77.

Table 77: Speed Control Strategies and Definitions

RTF Speed Control Definition	Speed Control Method	Definition
N/A	**Constant speed controls**	A control that adjusts the speed of the pump manually, typically to one of several discrete values, based on user input.
Differential pressure control*	**Constant pressure controls**	A control that automatically adjusts the speed of the driver in response to pressure in order to maintain a constant system pressure.

RTF Speed Control Definition	Speed Control Method	Definition
	Proportional pressure controls	A control that automatically adjusts the speed of the driver in response to pressure along a preset control curve that decreases system pressure as speed decreases.
Adaptive pressure controls	**Adaptive pressure controls**	A pressure control that continuously senses the head and flow requirements in the system in which it is installed and adjusts the control curve of the pump accordingly.
Differential temperature control	**Differential temperature controls**	Temperature control means a control that automatically adjusts the speed of the driver continuously over the driver operating speed range in response to temperature.
* The RTF defines Differential Pressure Control as a control (variable speed drive and integrated logic) that automatically adjusts the speed of the driver in response to pressure in order to maintain a constant system pressure.		

5.4.1.2 Domestic Hot Water Recirculation

The RTF Measures for DHW recirculation present energy savings estimates based on timer controls, and do not specify the speed controls of a pump. However, throughout site identification and data collection, the research team evaluated several sites are employing speed controls in DHW applications in order to reduce the power consumption of the pump and potentially reduce the average loop temperature of the recirculation loop. The research team also observed several different variations of on-demand controls or multiple control strategies being operated together. The unique run-hour DHW controls observed in the research, as compared to those listed in the RTF Research Plan, along with their definitions, are listed in Table 78. All of the speed control varieties listed in Table 77

Table 78: Run-Hour Control Strategies and Definitions

RTF Control Strategy	Observed Control Strategy	Definition
N/A	Timer Control	A schedule-based control that allows the user to turn on and off the pump at pre-set times and/or for a set amount of time.
	Timer Control with On-Demand Functionality	A schedule-based control that initiates pump flow based on sensing the presence of a user of a fixture (i.e., on-demand control) OR if the pump has been idle for a set period of time.
Aquastat	Aquastat	Temperature control that automatically turns off the pump based on the temperature in hot water distribution piping. *Note, Aquastats may also incorporate some on-demand functionality that initiates pump operation based on sensing the user of a fixture, in addition to the temperature in the piping.*
Learning	Learning	Control that develops a schedule of operation based on actual use patterns, which are determined based on sensing the presence of a user of a fixture.

RTF Control Strategy	Observed Control Strategy	Definition
On-demand	On-demand	A strategy the follows the following sequence: 1. Initiates water circulator based on receiving a signal from the action of a user (of a fixture or appliance) or sensing the presence of a user of a fixture and cannot initiate water circulation based on other inputs, such as water temperature or a pre-set schedule. 2. Automatically terminates water circulation once hot water has reached the pump or desired fixture. *Note: this includes both proactive on-demand controls, which identify the future need for hot water typically based on a manual button/switch or occupancy sensor, and reactive on-demand controls, which initiate flow based on the use of hot water somewhere in the building.*

5.4.1.2.1 On-Demand Controls

On-demand controls in the single-family residential sector are applied in a manner consistent to the definition in Table 78. They initiate pump operation when there is a demand for water and stop pump operation when hot water has reached the tap (as indicated based on a high-temperature cut-out on the return water line). The difference in control methods available in this sector is related to the method for detecting flow. There are two different methods for detecting “the user of a fixture”: 1) a manual button or a motion sensor that starts the pump before hot water is needed at the fixture and 2) a flow sensor which senses flow when a fixture is opened and starts the pump after hot water is needed.

This research has classified the first method of detecting “the user of a fixture” as **predictive on-demand** because the pump is initiated before hot water is needed, so no cold water is wasted waiting for hot water. The second method of detecting “the user of a fixture” based on flow is classified as **reactive on-demand** because the pump starts as a reaction to the need for hot water, therefore cold water is wasted waiting for hot water, but it is less than would be without the recirculation pump (due to the higher flow rate with the pump operating). While both of these control methods have the potential to save water, predictive on-demand is a more effective way of preventing water and associated energy waste.

Commercial on-demand systems are more complicated to implement than residential on-demand because of the scale of the recirculation loops and hot water requirements in this sector. Due to the large size of recirculation loops found in commercial buildings, there can often be a large volume of water between the water heater and the user of a fixture that cannot be effectively evacuated in a reasonable amount of time, even with predictive on-demand controls. This can result is tap temperatures that are far below the temperature needed and/or wait times that are much longer than users can reasonably be expected to tolerate. Commercial buildings are also required to serve the tenets of the facility (whether it be a hotel or office space) and the potential for creating a long wait for hot water is often not employed to avoid customer dissatisfaction.

To achieve energy savings from recirculation pump controls *and* avoid jeopardizing customer satisfaction manufacturers are developing and implementing controls that do not allow the loop temperatures to drop below unacceptable limits. Pump manufacturers have accomplished this by coupling some on-demand control functionality with a low-temperature limiter which initiates the pump based on water temperature, or on-demand control features with a schedule function which initiates the pump if it has not run in a specified amount of time. All commercial sites that the research collected that employed "on-demand" controls also had an additional function that prevented the loop from cooling down. This function disqualified them from being considered "on-demand" controls in this research, as the RTF definition for on-demand stipulates that the pump cannot be started by an input other than demand for water. The pumps collected that employed a version of commercial on-demand with additional either temperature or scheduled-based initiation are classified as "Aquastat" or "timer control with on-demand functionality," respectively.

5.4.1.2.2 Aquastat Controls

Aquastat controls operate, in both the single family and commercial sector, similarly. Both employ temperature sensors on the return water line to start and stop the pump based on temperature. Aquastat controls produce energy savings in a similar manner to on-demand controls, by decreasing the run-time of the pump to only when it is needed. The main difference between the two controls is the factor indicating "need". With on-demand controls the "need for water" is indicated by sensing a user at a fixture whereas the "need for water" in Aquastat controls is defined by the temperature of the loop dropping below a set temperature.

In the commercial sector Aquastat controls are often-time conflagrated with on-demand controls because both operate the pump not based on a set schedule but based on a "need for water". This, coupled with the fact that Aquastat controls are often coupled with other control strategies (Aquastat with boiler temperature modulation, Aquastat with a schedule timer, etc.), lead to confusion at the sites monitored as to the control strategies used.

5.4.1.2.3 Learning Controls

This research was only able to collect and identify one pump with learning controls. This pump was installed in single-family residential sector. There are currently only two manufacturers that feature learning-based controls, both of which are designed for the residential sector. These are also relatively new controls that are not widely available in the stock, so had to be specifically retrofit by the research team. For these reasons, it was challenging to collect sufficient data to effective evaluate these new controls and the research team recommends further evaluation as part of a future research effort to better understand their control logic and energy consumption characteristics.

In the commercial and multi-family sectors, learning controls are less applicable due to the variable and unpredictable usage patterns that may jeopardize hot water delivery. Further, in commercial office space it is more likely that schedule controls will be employed because of consistent occupancy patterns. An office building usually follows the same pattern of occupancy from week to week, and tenets in these buildings are already agreeing to service setbacks (such as no air-conditioning on the weekends or increased security during unoccupied times) that a recirculation pump schedule controller can match.

5.4.2 Operating Hours

The Research Team started the operating hours analysis for both Circulator applications by calculating the observed operating hours for each control method and comparing them to the estimates made in the RTF Measures. After the high-level comparison the research team investigates variations in each application to determine if the data suggested a different disaggregation.

5.4.2.1 *Domestic Hot Water*

The research collected a total of 90 circulators in the Domestic Hot Water Application with enough audit information to calculate operating hours. The circulators operated under various control methods, some not represented in the RTF Measures.[62] Table 79 shows the observed operating values for each run-hours control method evaluated in the research, along with the associated estimates made by the RTF, if applicable. As mentioned previously, the research team observed some DHW circulators that featured speed controls. Since speed controls do not have an impact on operating hours (the controls modulate speed to provide a given return temperature or duty point, but maintain operation of the pump), all circulators with speed controls are listed in the "No Controls" portion of the table.

Table 79: DHW Circulator Operating Hours, Observed vs RTF Estimate

Sector	Run-hour Control Variety	Average Operating Hours	n	Std Deviation	Standard Error	90% Margin of Error	90% Confidence Interval	RTF Estimate
Residential	No Control	8,760	5	-	-	-	8760 to 8760	8,760
	Timer Control	3,469	2	2,501	1,768	2,917	551 to 6386	7,300
	Aquastat	3,913	5	3,809	1,703	2,810	1102 to 6723	1,095
	On-Demand	60	1	-	-	-	60 to 60	61
	Learning	-	0[63]	-	-	-	-	1,095
Commercial	No Control	8,218	51	1,842	258	426	7792 to 8643	8,760
	Timer Control	3,681	13	2,132	591	975	2705 to 4656	6,570
	Aquastat	1,239	8	1,218	431	711	528 to 1950	1,095
	On-demand	-	0	-	-	-	-	122
	Timer Control with On-Demand Capabilities	274	4	43	21	35	239 to 309	NA
	Learning	-	0	-	-	-	-	1,095

The observed and RTF-estimated hours for "No Control" are close for both commercial and residential, with the RTF estimating full year operation and the observed values falling within 1% of this value for both sectors. For other control strategies, the values observed for operating hours in each sector and control strategy are different than the RTF estimates; however, the relationship between control strategy and operating hours is consistent between the two: Timer controls have the most operating hours after no controls, followed by Aquastat, then schedule-based with on-demand capabilities. The RTF estimated the same operating hours for Learning as Aquastat, but the only pump that this research observed with Learning Mode had a logger failure and was only able to collect loop temperature data.

The operating hours for timer controls observed in this research was significantly lower than that estimated by the RTF and DOE. DOE and the RTF's estimates may have been conservative, assuming that users would set the schedule-based controls to ensure maximum hot water delivery and ensure occupant

[62] Control Methods for DHW Circulators seen in the data collected but not included in the RTF measures include Schedule-based control with on-demand capabilities, as well as several speed control methods (i.e. Temperature-based control, Adaptive Pressure control, and Constant Pressure control).

[63] While the research did collect data on one Residential learning site the logger tracking operating state failed and operating hours were not able to be calculated.

satisfaction[64]. This research found that run-hours-based controls are an effective energy reduction strategy and can reduce operating hours more than 50% compared to the 24/7 baseline case in both residential and commercial settings.

The operating hours for Aquastat observed in the research were higher than the operating hours estimated by the RTF, especially for the residential sector. In the commercial sector only one true Aquastat was monitored, where Aquastat is defined as a pump that is turned on when the return temperature reaches a low-temperature setpoint and is turned off when the temperature reaches a high-temperature set-point; the other 7 pumps listed as Aquastat utilized a timer-based Aquastat, which turned the pump on every 30 minutes and operated the pump until the setpoint temperature was met. While this "timer-based Aquastat" is not a "true Aquastat", it still falls under the RTF's definition of an Aquastat: "Temperature Controls that automatically turns off the pump based on the temperature in the hot water distribution piping" (Tingleff, Widder and Hadley 2017). The RTF's estimates were based on 3 hours of operation per day, and the observed operating hours reflect approximately 11 hours of operation per day. This may be due to higher usage or loop losses than previously anticipated, and/or the timer-function associated with the timer-based Aquastat pumps.

For on-demand controls, the operating hours observed in the residential sector where very close to the estimate made by the RTF, which is based on 10 operating minutes per day. As discussed in Section 5.4.1.2.1 there were no instances of qualifying commercial on-demand controllers. The average observed operating hours for schedule based with on-demand capabilities is 274 hours. While this is only 152 hours more than the RTF estimate for commercial on-demand, the RTF estimate is less than half of the observed value. The RTF based its estimate on the assumption that the pump operates 20 minutes per day. The incorporation of the "5-hour operation start" as well as on-demand controls may be driving up the observed operating hours, causing this difference.

5.4.2.2 Hydronic Heating

The research collected data on 24 hydronic heating Circulators. The data was collected from multiple geographic locations in the Northwest, and the observed operating hours were normalized, based on Heating Degree Days (HDD), to the average HDD's of all hydronic heating circulators collected for the research (5,428 HDD). All hydronic heating operating hours values presented in this section are normalized to this value. Table 80 shows that the average operating hours for residential Circulators is approximately 800 hours higher than for commercial Circulators. This is counter to the estimate the RTF made, which estimates residential circulators to have 2,605 operating hours. The observed operating hours corresponds to 4.5 months of operation in one year, whereas the RTF estimate corresponds to approximately 3.5 months of operation per year. The RTF developed their estimate based on 0.33 hours/HDD. The observed hours correspond to 0.42 hours/HDD. As discussed in Section 5.2.3.1.1 the team removed the Commercial sector for the hydronic heating sample frame, but included it in the analysis (in grey in Table 80).

[64] The RTF assumed 50% of timer-controlled systems would operate 24/7 and 50% would operate for 16 hours/day

Table 80: Observed Operating Hours, Hydronic Heating

Statistic	All HH Pumps, Observed	Residential Pumps, Observed	Commercial Pumps, Observed
No. of Pumps in the sample	24	21	3
Average	**3,008**	**3,109**	**2,298**
Max	8,634	8,634	6,054
Min	-	137	-
Standard Deviation	3,059	3,098	3,280
Standard Error	624	676	1,894
90% Margin of Error	1,030	1,116	3,124
90% Confidence Interval	1,977 to 4,038	1,993 to 4,225	-826 to 5,423

The RTF also estimated the operating hours for constant speed and variable speed Circulators. The RTF estimated that variable speed circulators would operate for more operating hours than their constant speed counterparts due to lower flow rates and reduced heat transfer through emitters. However, Table 81 shows that the variable speed pumps collected in this research operating, on average, almost 1,100 hours less than constant speed pumps. However, due to the small sample sizes and variability in the data, the difference between constant speed and variable speed pumps is not statistically significant. If real, the research team hypothesizes that pumps with speed controls may enable more precise temperature control that limits temperature swings and results in overall less energy consumption and pump operation.

Table 81: Observed Operating Hours, Hydronic Heating by Speed Control Method

Statistic	Constant Speed	Variable Speed
No. of Pumps in the sample	13	11
Average	3,721	2,623
Max	8,760	8,760
Min	-	165
Standard Deviation	3,744	3,191
Standard Error	1,038	962
90% Margin of Error	1,714	1,587
90% Confidence Interval	2,008 to 5,435	1,036 to 4,211

According to Table 81 the difference between the Constant Speed and Variable Speed hydronic heating circulators isn't statistically significant. To investigate the difference more directly the research team calculated operating hours on circulations where constant and variable controls on the same systems. There are 5 Circulators that operated with both constant and variable speed controls. Three out of these 5 sites saw the speed decrease with a change from constant to variable speed control, one pump saw no change (with the pump operating all year) and one pump, Pump 1 shown in Table 82, increased. While the operating hours of this pump did increase, the increase is a small absolute difference compared to the differences of operating hours of the other pumps in this table, and the research team believes the difference is not significant.

Table 82: Operating Hours - Hydronic Heating Circulator replacement

Pump	Constant Speed	Variable Speed	Percent Difference
1	280	480	Not Statistically Significant
2	8,760	8,760	0%
3	3,828	1,338	65%
4	6,876	3,547	48%
5	8,760	1,426	84%

5.4.3 Average Operating Power

The average operating power of all the Circulators collected for this research was analyzed by the research team. Table 83 shows the average operating power, by nominal HP and Efficiency Level (the efficiency level definitions are included in Table 84). Table 83 also includes EL2.5, which represents Constant Pressure Controls which the RTF measures do not include. The broad range of Nominal HP's and Efficiency Levels meant getting a representative sample in each EL/Nominal HP configuration was not feasible. The research team decided to average the operating power for each Efficiency Level (weighted by the number of pumps in each Nominal HP) and normalize the values to 1/25 HP. These values are presented in Table 84, along with the RTF Estimated values.

Table 83: Average Operating Power (Watts), by Nominal HP and Efficiency Level

Nominal HP	1/40	1/25	1/12	1/6	1/4	1/2	3/4	1	1.5	2
EL0	43	88	139	158	418	367	1,176			1,373
EL1										
EL2	15	31	102							
EL2.5	25	39	56							
EL3	11	19	24							
EL3.5	10		12	22						
EL4		10	33	19						

Table 84: Weighted Average Operating Power, (Watts for a 1/25 HP circulator)

EL	Description	Weighted Average Power, normalized to 1/25 HP		
		Observed Watts	n	RTF Estimate (Watts)
EL0	**Induction Motor**	62	44	116
EL1	**Efficient Induction Motor**	NA	NA	88
EL2	**ECM**	34	8	51
EL2.5	**ECM with Constant Pressure Controls**	34	8	NA
EL3	**ECM with Proportional Pressure Control**	16	5	41
EL3.5	**ECM with Adaptive Pressure Control**	10	10	38
EL4	**ECM with Differential Temperature Controls**	11	10	30

Table 84 shows that the average power of the observed pumps is much lower than the average power of the RTF estimates, but the relationship between the efficiency levels and the difference from EL0 is consistent between the two data sets. The observed pumps show that the induction motor (EL0) operates at a power 160% higher than an ECM. This is close to the RTF estimate of 130%. The operating power seems to see two stepwise decreases, one between EL0 and EL2 (The switch from an induction motor to an ECM) and between EL3 and EL3.5 (the switch from fixed to more advanced/adaptive speed control approaches).

One reason for the discrepancy in magnitude between the observed values and RTF estimate may be due to the load profile assumed in the RTF calculation of average power. The RTF uses the equations laid out by the Circulator Working Group to calculate PER, which represents the weighted average power of the circulator over an assumed load profile. This calculation method assumes equal weighting of 4 different load points (25%, 50%, 75%, and 100% of BEP) for constant speed circulators and an operating hours distribution of 5%, 40%, 40%, and 15% between 25%, 50%, 75%, and 100% of BEP, respectively, for variable speed pumps.

To investigate this, the research team calculated the load profile for all circulators submitted with flow data and compared them to the RTF load profile assumptions from the DOE Circulators working group. The research team determined the amount of time each circulator spent at 25, 50, 75, and 100% of BEP flow. However, since circulator pump curves are most often published without the efficiency curve or information on BEP, in some cases, the research team had to make assumptions regarding the “BEP” of the pump that would correspond with the 100% flow point. Specifically, the circulator manufacturer Grundfos has an interactive online “Product Center”[65] that allows a user to select different operating points to review the corresponding pressure. The Product Center also features a “nominal operating point”, which auto-selects an operating point on the curve. For all Grundfos pumps that did not have a specified flow at BEP the “nominal operating point” flow was used as BEP. For the Grundfos pumps and all

[65] Grundfos’ Product Center can be accessed at https://product-selection.grundfos.com/

pumps with information on BEP the team then calculated BEP as a percent of Max Flow. The average of these values, 44% of Max flow, was used to calculate an approximate BEP for all circulators that did not have information on BEP. The percent of operating hours spent at each load point was then calculated for each pump.

Table 85 presents the average load profile for all the circulators load profile was calculated for, along with the average load profile for each efficiency level. The average load profile for all circulators is not drastically weighted to one point in the load profile (~60% of the time spent below 50% of Flow at BEP, ~40% spent above), but when broken out by efficiency level a marked difference between constant speed circulators (EL0) and variable speed circulators (EL2[66] through 4) presents itself. The constant speed circulators operating hours are concentrated at the higher end of the load profile, spending 62% of their time, on average, above 75% flow at BEP. Variable speed circulators, by contrast, spend 51% of their operating hours at or below 25% flow at BEP and only 3% of their operating hours above 75% flow at BEP. This pattern of higher average operating points for constant speed circulators and lower average operating points for variable speed circulators holds true when the circulators are broken out by application, as shown in Table 86 and Table 87.

Table 85: Circulator Load Profile by Efficiency Level, all Circulators

	Under 25% of BEP Flow	Between 25% and 50%	Between 50% and 75%	Between 75% and 100%	Between 100% and 110%	Above 110%	n	Average HP	Average Flow Rate (gpm), Normalized to 1/25 HP
All Circulators	33%	28%	10%	5%	3%	22%	**73**	**1/7**	**4.30**
EL0	10%	19%	9%	10%	6%	46%	**32**	**1/4**	**6.16**
EL1	0%	0%	0%	0%	0%	0%	**0**	-	-
EL2	42%	49%	8%	1%	0%	0%	**8**	**1/25**	**1.95**
EL2.5	42%	38%	20%	0%	0%	0%	**8**	**1/18**	**3.39**
EL3	27%	71%	2%	0%	0%	0%	**5**	**1/18**	**3.51**
EL3.5	61%	26%	3%	0%	0%	10%	**10**	**1/13**	**3.80**
EL4	69%	9%	18%	4%	0%	0%	**10**	**1/13**	**1.86**

[66] EL2 is defined in by the RTF as an "ECM with no control". As ECMs are by nature variable speed motors, most all circulator manufacturers baseline ECM model includes at the very least 3 speed options. These circulators with 3-speed options, or Fixed Speed Circulators, are classified as EL2 and while they are not continuously variable speed controls, the ability to vary the speed of EL2 circulators classifies them as Variable Speed Circulators.

Table 86: Circulator Load Profile by Efficiency Level, Hydronic Heating

	Under 25% of BEP Flow	Between 25% and 50%	Between 50% and 75%	Between 75% and 100%	Between 100% and 110%	Above 110%	n	Average HP	Average Flow Rate (gpm), Normalized to 1/25 HP
Hydronic Heating	34%	34%	15%	3%	5%	10%	**20**	**1/10**	**2.95**
EL0	19%	9%	13%	0%	20%	40%	**5**	**1/5**	**5.56**
EL1	0%	0%	0%	0%	0%	0%	**0**	**-**	**-**
EL2	35%	47%	16%	3%	0%	0%	**4**	**1/20**	**2.21**
EL2.5	45%	33%	21%	0%	0%	0%	**3**	**1/20**	**3.57**
EL3	23%	77%	0%	0%	0%	0%	**2**	**1/16**	**2.94**
EL3.5	60%	34%	7%	0%	0%	0%	**4**	**1/15**	**0.78**
EL4	10%	30%	41%	20%	0%	0%	**2**	**1/25**	**1.29**

Table 87: Circulator Load Profile by Efficiency Level, Domestic Hot Water Recirculation

	Under 25% of BEP Flow	Between 25% and 50%	Between 50% and 75%	Between 75% and 100%	Between 100% and 110%	Above 110%	n	Average HP	Average Flow Rate (gpm), Normalized to 1/25 HP[67]
Domestic Hot Water	33%	25%	8%	6%	2%	26%	**53**	**1/6**	**4.81**
EL0	8%	21%	8%	12%	4%	47%	**27**	**1/4**	**6.27**
EL1	0%	0%	0%	0%	0%	0%	**0**	**-**	**-**
EL2	49%	51%	0%	0%	0%	0%	**4**	**1/30**	**1.70**
EL2.5	40%	40%	20%	0%	0%	0%	**5**	**1/18**	**3.28**
EL3	30%	67%	3%	0%	0%	0%	**3**	**1/20**	**3.90**
EL3.5	62%	22%	0%	0%	0%	17%	**6**	**1/12**	**5.81**
EL4	84%	4%	13%	0%	0%	0%	**8**	**1/12**	**2.00**

Table 85, Table 86, and Table 87 also show the average motor HP for each efficiency and the average flow rate, normalized to 1/25 HP. The average nominal HP for constant speed circulators is larger by a factor of at least 3. This, coupled with the fact that the average flow rate (when normalized to 1/25 HP) for

[67]It should be noted that Table 85, Table 86, and Table 87 include both commercial and residential circulators, and a larger percentage of EL's 2-4 are single family residential sites. This may be impacting the Average flow rate through the systems and can be investigated in future projects.

constant speed pumps is almost double that of the variable speed pumps, indicates that end-users are oversizing constant speed circulators when installing them and the constant speed operation is providing more recirculation than needed. When variable load pumps are installed, the pumps are able to provide more appropriate flow rates and account for this oversizing, which may also be contributing to reduced load profile and average power values compared to the RTF assumptions.

As the EL of the variable speed pumps increases, the load profile concentrates at lower operating points. This could possibly be due to two reasons: 1) manufacturers have noted that with more advanced speed controls (adaptive pressure and differential temperature) they are consolidating their circulator lines to fewer sizes because of the control strategies or 2) the more advanced control strategies (adaptive pressure and differential temperature) adjust flow to the needs of the system instead of adjusting pump operation to meet a pre-programed pressure point.

When comparing the estimated load profile used to calculate the weighted average input power by the RTF, the weighted average load points for the constant and variable speed circulators is 63% flow at BEP and 66% flow at BEP, respectively. When calculated using the load profiles presented in Table 85 the weighted average load points for constant and variable speed circulators are 91% flow at BEP and 42% flow at BEP. For variable speed pumps, much of the difference in observed versus estimated average power could be attributed to the difference in observed versus estimated load profile, since changes in flow rate result in a cubic increase or decrease in power, as shown by the affinity law relationships in Equation 27,

$$\frac{P_1}{P_2} = \left(\frac{N_1}{N_2}\right)^3 \quad (27)$$

$$\frac{N_1}{N_2} = \frac{Q_1}{Q_2}$$

where

P = Brake HP
N = Rotational speed of the pump
Q = Flow through the pump

For constant speed pumps (EL0) this difference in load profile does not explain the difference between the estimated vs observed average power. Based on load profile we would expect the observed average power to be higher. Possible causes for this difference could be that the RTF is simply overestimating the power consumption of induction motors. Along with this, the research was not able to clearly differentiate between EL0 and EL1 (induction motors and induction motors with increased efficiency) and the inclusion of more efficient induction motors may be decreasing the observed average power.

The research team also reviewed the decrease in average power (or percentage savings) from more efficient pump controls in comparison to less efficient pumps. The team used two baselines, presented in Table 88, to compare pump power. The first baseline is EL0, or an induction motor with no controls. The second baseline is an ECM with no controls, or EL2. The first baseline represents the decrease in power consumption in relation to the least efficient option, whereas the second baseline shows the decrease in power due solely to the implementation of controls. From EL0 the average power decreases from 67% at

EL2 to 84% at EL4. EL2 and EL2.5 are within 2% of each other, and E3, EL3.5, and EL4 are within 3% of each other at a lower power draw.

Table 88: Average Percent Decrease in Power for Pump Swaps

Baseline	Efficiency Level	Percent Decrease in Power	n	Min	Max	Standard Deviation
From EL0	**EL2**	**67%**	2	63%	72%	6%
	EL2.5	**65%**	4	22%	94%	31%
	EL3	**86%**	3	82%	91%	5%
	EL3.5	**83%**	6	53%	95%	19%
	EL4	**84%**	9	40%	96%	18%
From EL2	**EL2.5**	**41%**	2	26%	57%	22%
	EL3	**60%**	2	43%	76%	24%
	EL3.5	**41%**	2	30%	53%	16%
	EL4	**58%**	2	55%	61%	5%

With a no-control ECM as baseline the average power for all the pumps and controls is lower than without. The data collected is showing that Adaptive Pressure, EL3.5, uses more power than proportional pressure, EL3. The research team identified 2 possible reasons this is presenting itself: 1) When the pumps optimize they start at a conservative operating point and migrate to the most efficient location on the system curve. The research may have not allowed the pump enough time to optimize. 2) The optimum operating point was established for these systems at a higher point than the proportional pressure.

The proportional pressure and differential temperature control strategies (EL3 and EL3.5, respectively) are showing comparable decreases in power consumption. While the data are showing no significant difference in power between the two control strategies, differential temperature does have the benefit of benefiting boiler efficiency.

5.4.4 Water Heater Energy Savings

This research addressed water heater energy savings through monitoring the change in loop losses on the same system with various control strategies. The research collected data from 20 different sites that cycled through control strategies on the same system. This allowed the research team to hold all variables on energy use constant and investigate the changes in water heater energy use due to control strategy.

The research team collected supply water temperature and return water temperature on the recirculation loops each pump was installed on. The supply water temperature is the water temperature at the beginning of the recirculation loop, right after the water leaves the water heater. When the recirculation circulator is operating the supply water temperature is very close to the water heater temperature. When the pump is off the water in the entire loop is stagnant, so the supply water temperature will decrease to the ambient temperature of the building. The return water temperature follows a similar pattern, where the temperature is highest when the pump is running and drops to near room temperature when the pump is off. Because heat losses occur both when the pump is running and when the pump is off, the method for calculating water heater savings has to address the heat lost to through the loop during both periods.

The research team accomplished this by looking at the average loop temperature throughout the year for different control strategies. The average loop temperature at any given point in time is the average of the supply temperature and the return temperature. On a system with speed controls, changes to the controls have the ability to drive the return temperature down by decreasing the flow of water through the system. This would decrease the average loop temperature. On a system with run-hours controls, reductions in pump operation will cause the entire loop to cool, which will reduce the average annual loop temperature. Comparing the average loop temperature values between control strategies on the same system allows for the energy savings associated with optimizing the operating point to be investigated.

To aggregate 8,760 instances of average loop temperature into a comparable value for each pump the research team used the average of all the average loop temperatures throughout the year. When compared on the same system this value is proportional to both a change in speed control (which will decrease or increase the average loop temperature) and a change in run-hours control (which will increase or decrease the amount of time the loop spends at or approaching room temperature). There were certain where controls were switched but no baseline temperature data was collected. For these sites the research team used the average supply temperature for the efficient control strategy pumps as the baseline supply temperature. The average percent difference between supply and return temperature in pumps without controls in the same sector was calculated and applied to the baseline supply temperature to calculate a return temperature for these pumps.

There are 56 total Circulators in the Hot Water Savings analysis. Table 89 presents the percent energy savings, separated by sector and control method. The RTF Measures only address Hot Water energy savings on Timer Controls, but the research team was able to collect data on pumps with run-hours controls, with speed controls, and with a combination of both run-hours and speed controls.

Table 89: Percent Hot Water Energy Savings, by Sector and Control Strategy

Sector	Speed Control	Timer Control	% Energy Savings[68]	n
Single Family Residential	No Control	No Control	-	3
	No Control	Learning	37.08%	1
	No Control	Temperature	6.49%	5
	Adaptive Pressure	No Control	7.91%	1
	Differential Temperature	No Control	0.29%	1
Multi-Family Residential	No Control	No Control	-	8
	No Control	On-Demand*	15.52%	4
	No Control	Temperature	14.54%	1
	Constant Pressure	No Control	4.98%	1
	Proportional Pressure	No Control	6.29%	2
	Adaptive Pressure	No Control	1.05%	3
	Differential Temperature	No Control	0.16%	1

[68] The number of places after the decimal point in this column was increased to allow for comparison of the pumps that had less than 1% Energy Savings

Commercial	No Control	No Control		6
	No Control	On-Demand	1.35%	1
	No Control	Timer	14.57%	3
	Constant Pressure	No Control	2.62%	2
	Proportional Pressure	No Control	2.45%	1
	Differential Temperature	No Control	3.72%	3
	Constant Pressure	Timer	4.25%	2
	Adaptive Pressure	Timer	4.38%	2
	Differential Temperature	Timer	0.90%	4

*All multifamily On-demand Circulators in this table are Fixed Speed Temperature Based On-Demand

From the data collected it is evident that run-hours controls were more effective in driving water heater energy savings than speed controls. Timer controls saved, on average, 13% of the water heater energy, whereas the speed controls saved only an average of 3% water heater energy savings.

The differential temperature speed controls, across all three sectors, showed very little hot water energy savings. These controls do not ever tur off the pumps, so the beginning of the loop is always hot, and the entire loop is not allowed to cool down. The system is then constantly loosing heat, so the low energy savings is not unexpected. Timer- based temperature controls allows the entire loop to cool down by stopping the pump. This means hot water is not constantly reheating water.

The relative efficacy of each control type varied by sector, but due to small sample sizes and variability between the sites it is difficult to reach conclusive findings related to the absolute impact of different control strategies on water heater energy consumption.

5.4.5 Additional Insights

The research team monitored 90 circulators for the research. Through the site identification, coordination, and data collection the research team installed 15 new circulators at 11 sites. The team installed 4 different brands of Circulators with an array of controls available. The goal of the pump installation, as mentioned in Section 5.2.1.2, was to provide the ability to cycle through control methods and determine the effect each control method has on the system. This interaction with end users (the people servicing the pumps and the people using the hot water or heated space) gave the research team the opportunity to investigate the implementation of controls and the reaction to each control method. While it wasn't the main goal of the primary data collection, the team did observe certain patterns in the interactions with the pumps and pump end users.

> The **Nomenclature** used to identify each control strategy is not consistent across the industry. Section 5.2.3.1.2 discussed the differences in how on-demand controls are implemented (with and without temperature limits). Often the term "Auto" will be used by a manufacturer and the literature does not specify whether it is Adaptive Pressure (where the pump *auto*matically sets the operating point or Learning (where the pump *auto*matically develops a timer schedule to turn the pump on and off based on use). "Temperature control" can also reference either speed controls (where the pump is slowed down or sped up to maintain a certain change in temperature across the recirculation loop) or Timer Control (an upper-temperature and lower-temperature limit is set and the pump is turned on and off to maintain the return temperature between these two values).

None of the end users mentioned a **Disruption in Service** or mentioned a change in the usual operation of their systems. A change in the comfort or convenience of the system is a factor that may prevent the adoption of the controls. At all 11 sites no end user mentioned that the different control strategies made a noticeable difference in either the hot water delivery or the space heating. This indicates that the control methods are not a noticeable part of either the Domestic hot water or space heating systems and the team did not identify a decrease in effectiveness related to different control strategies.

There was also no **Recidivism,** or return to a less efficient control strategy when the research team removed the metering. One of the keys to successfully achieving energy savings from Circulator controls is ensuring the are not getting bypassed or overridden. No sites requested that the pump control strategy be reverted to any specific strategy. When the metering was removed all pumps were left in the efficient control mode they were last metered in. This indicates to the research team that the control strategy that the pump is operating with when installed is most likely never adjusted.

The **Installed Control Strategies** for DHW Circulators, before retrofits were installed, was almost exclusively no control. There was one single family residential site that had advanced controls installed, but this was the home of a general contractor, and the mechanical system at the site is not representative of a normal home in the Northwest. For hydronic heating, the pumps were most often controlled via an interlock with the boiler and advanced controls were not present. The best way to address the research question related to the installed control strategies of circulators (discussed in Section 5.1.2) is through market research and interviews with installers, however this information indicates very little implementation of advanced controls.

6 Conclusions

This research set out to characterize pump operation in the Northwest, with the goal of validating the assumptions that went into the simplified energy consumption model developed for the RTF's UES Measures.

The results of this research show that the operating hours estimates made by the RTF are within 6.6%, 4.6%, and 1.8% of the observed operating hours for Commercial HVAC and DHW, Industrial, and Agricultural Irrigation, respectively. However, the analysis showed a large amount of variability between the Commercial HVAC and Commercial DHW applications. The Commercial DHW pumps operate 77% more time than the Commercial HVAC pumps. The data shows a similar trend between the Municipal and Industrial pumps. Industrial Pumps, on average, operate 84% more hours than Municipal pumps. While the observed operating hours averages, at the granularity set by the RTF, are consistent with the values established by the RTF, this research suggests a more robust disaggregation of operating hours would include unique operating hour estimates for Commercial HVAC Pumps, Commercial DHW Pumps, Industrial BFW Pumps, Industrial Cooling Pumps, Municipal Pumps, and Agricultural Pumps.

The Adjustment Factor compensates for real world pump operation, and the RTF made assumptions on four key sub-factors that were used in developing the Adjustment Factor values.

The RTF assumed a **Motor Oversizing** of 120% from pump power at BEP. This value is used across all motor HP's. The average motor oversizing seen in the pumps collected was 124%, with the RTF estimate falling into the 90% confidence interval of this data. This shows that the estimate made by the RTF was not inaccurate, however this research indicates that smaller motors are more oversized than larger motors, with the relationship between motor oversizing and motor HP tracking as exponential decay. When reviewed critically, the same absolute value difference in power between the pump and motor represents a larger percentage at small HP's than large HP's. A motor can be installed that is 2.5 HP Larger than the pump needs, at 5HP, but that increase is a motor oversizing of 150%.

The sector is the dependent variable establishing the RTF's **static head** estimate. Industrial, Municipal, and Agricultural pumps are assumed to operate with an average static head of 20% of head at BEP and Commercial pumps with higher static head, at 40% of head at BEP. This research corroborated the estimate that Commercial HVAC and DHW pumps would operate, on average, with higher static head than Industrial and Municipal pumps (Agricultural pumps could not be evaluated due to data limitations). The data collected showed Commercial pumps operated with static head equal to 35% of head at BEP where Industrial and Municipal pumps operated with static head of 22% of head at BEP. The research team looked at the static head of pumps disaggregated to the application level, but the sample size at the application level did not provide confidence in averages at that granularity.

The **BEP Offset** incorporated into the UES Measures is the same as DOE's estimated range of -25% to +10% of BEP. The research team investigated the BEP Offset values for the pumps collected and found an average offset of -17%, which is significantly lower than the median value assumed by DOE and the RTF. The range of the BEP Offset values observed in the data is quiet broad; for the range to cover 90% of the pumps in the sample it would have to be expanded to -76% to +52%; DOE's original range only covered 31% of the pumps that were analyzed.

Load Profile plays a large role in the Adjustment Factor because the Adjustment Factor compensates for the fact that PEI estimates that the load distribution is equal across the operating range. The RTF used DOE's load profiles to calculate the Adjustment Factors. This research shows that the RTF greatly overestimated the amount of time a pump spends at 100% BEP Flow. This indicates that end users often size pumps incorrectly for a given application. For both Constant Speed pumps and Variable Speed pumps the pumps spent more time above 100% BEP than the RTF predicted. Through discussions with manufactures they noted that when scoping pumps it is not uncommon to size them to operate above BEP so when they are turned down they approach BEP. The load profiles also vary by sector, with Municipal pumps operating closer to BEP flow, whereas Commercial and Industrial pumps are more commonly turned down to below 50% of BEP flow. This is predicted to be a factor of both sizing practices within the sectors (i.e., the purpose of Municipal Water Facilities is to move water, so more attention is paid to the sizing of a pump) and the size of the pumps (municipal pumps are often larger than commercial pumps and operating a large pump inefficiently is a more noticeable energy loss).

For Circulators the research focused on addressing pump and control operational characteristics. These focused on operating hours, average operating power, and water heater energy savings. The ability to toggle between control methods at sites was crucial in answering these questions.

The **Operating Hours** for Domestic Hot Water Recirculation Circulators observed through the research was consistent with the RTF for No Control, but varied for Aquastat, On-Demand, Timer, and

Learning. The research team did not observe or implement any control strategies that met the RTF definition of on-demand in multi-family or commercial settings, but did observe a variety of other control strategies implemented, including Aquastat-style controls, Timer controls (some with on-demand functionality), or temperature-based speed control. The control market for DHW pumps appears to still be emerging based on the wide variety and diversity of control approaches available and observed in the research. For hydronic heating systems the observed operating hours for residential pumps was 3,291 hours, which equates to 4.5 months of operation per year. This is higher than the 3.5 months originally estimated by the RTF. Commercial Hydronic heating circulators are very uncommon in the field; most often the systems are served by nominal HP Clean Water Pumps so this research removed them from the sample frame.

The **Average Operating Power**, in Watts, for circulators with different efficiencies and speed controls was significantly lower than the RTF Estimate. This is due to differences in the observed load profile compared to that assumed by the RTF average power estimate. Variable speed circulators, especially, spend almost all their time below 50% of BEP flow, likely due to a combination of motor and pump oversizing and the ability of more advanced variable speed control to more closely match the load for the given application. The relative efficiency of the different control strategies was, however, similar with the RTF assumptions, with significant energy savings seen moving from an induction circulator to an ECM circulator, and then again from adding more advanced variable speed control to the ECM circulator. This may indicate a larger potential for energy savings with more efficient controls that originally anticipated.

The **Water Heater Energy Savings** observed in the research were the greatest for run-hours based control strategies, as opposed to speed control strategies, which is not surprising considering that speed controls will continue to circulate hot water in the loop constantly. The relative efficacy of each control type varied by sector, but due to small sample sizes and variability between the sites it is difficult to reach conclusive findings related to the absolute impact of different control strategies on water heater energy consumption.

The research team also gathered **Additional Insights** related to circulator controls throughout the process of conducting the research. In general, the research team found that the efficient controls tested were well accepted by users and provided the same level of service as the base-case controls. However, the research team observed very little penetration of these efficient controls in the field and a lack of consistency regarding the nomenclature used to refer to different run-hours and speed controls, which creates confusion in the marketplace and may work against long term market acceptance.

This research represents an important contribution towards better understanding and characterizing pump operation and energy consumption in the Pacific Northwest. Based on these findings, the research team recommends revisiting the Clean Water Pumps and Circulator Pumps measures to incorporate the updated findings and dependencies to improve the energy savings estimates, especially for Clean Water Pumps. For Circulator Pumps, given the variety of applications and diversity of control strategies, it was more difficult to accurately characterize the improvements from different control strategies and additional research may be needed in some areas, especially multi-family hydronic heating, in order to further inform the potential energy savings from the variety of control strategies offered by manufacturers. This report also only represents the first step in analyzing the wealth of pump data collected as part of this research and the research team looks forward to additional findings from future researchers who may leverage the database to answer additional questions.

7 Acknowledgements

Without the support and assistance of many dedicated individuals and groups this research would not have been possible.

First, the research team would like to acknowledge the members of Cadeo Group that supported the collection and data analysis, especially Rob Carmichael, Elizabeth Daykin, Fred Schaefer, and Marissa Meyers.

The Energy350 team worked tirelessly to identify, coordinate, and collect data from the primary data collection sites. A specific thanks goes out to Jeff Davis, Josh Weissert, Andy Krall, Jordan Pratt, Scott Jasinski, Channing Hunter, Ross Charland, Matt Lucas, Kelson Redding, Gregory Annis, Gertrude Villaverde, Adam Scherba, Phillip Maddi, Jerrine Wong, Justin Hovland, and Chris Smith.

All Existing Data Contributors were pivotal in completing this research. Without their support the data would have been inaccessible. These individuals include Larry Acker, Todd Amundson, Tunji Asiwaju, Shan Belew, Nick Carew, Chao Chen, Melanie Danuser, Nancy Goddard, Allison Grincell, Lucie Huang, Gary Klein, Duane Lewellen, Bill Livoti, Norm Mentor, Patrick Moore, Tom Osborn, Nina Pirofovsky, Chris Wanner, Dalton Weese, Jim White, and Randy Yoshimora.

The Primary Data Contributors were kind enough to allow the research into their facility or home, and the team would like to thank them profusely for this. A special thanks goes out to Wayne Alvarez-Rojas, Mike Branes, David Brant, Ben Bronson, Kevin Brooks, Joe Burks, Marc Compton, David Crider, Vlad Davidovich, Demian Davis, Adam Elliot, Marty Gleaves, Kent Hubbard, Jamie Huscroft, David Kroening, Don Larrison, Scott Lege, Pete Lepschat, Matt Lichtenfels, Justin May, Bill Naito, Nao Ohdera, Ken Packwood, Kevin Sawyer, Dirk Theisen.

The Technical Work Group dedicated multiple hours across the entire duration of the research to review, support, and inform the research development and execution. Their support was invaluable. Thank you to Brent Ross, Gabor Lechner, Andy Paul, Erin Hope, Todd Amundson, Kenji Spielman, Chris Ireland, Devin Carle, Edgar Suarez, Randy Thorn, Nicholas Ricciardi, Melanie Danuser, Kevin Smit, Patrick Moore, Nancy Goddard, Christian Douglass, Jim White, Chao Chen, John Owen, Lucie Huang, Allison Grinczel, Jim Conlan, Rick Rosenkilde, Mark Chaffee, Matthew Walker, and Shari Kelley.

Finally, the members of the pump industry went over and above in support of this effort, and a thank you goes out to Brent Ross of Armstrong Pumps, Chris Jostol of Mechanical Sales, Mark Hanzel of Xylem, Mark Chaffee of Taco, Gary Babb of PacWest Sales, and Brad Jacobs of Grundfos.

8 References

Ally, M. R., J. J. Tomlinson, and B. T. Ward. 2002. *Water and Energy Savings using Demand Hot Water Recirculating Systems in Residential Homes.* Palo Alto: Oak Ridge National Lab.

Arena, O, and L Faayke. 2013. *Optimizing Hydronic System Performance in Residential Applications.* Washington DC: DOE Building Technologies Office.

ASRAC. 2016. "Circulator Pumps Working Group Term Sheet." https://www.regulations.gov/docket?D=EERE-2016-BT-STD-0004 , September 7.

Dean, Jesse, Anoop Honnekeri, and Greg Barker. 2018. *High Performance Circulator Pump Demonstration.* Field Study, Denver: National Renewable Energy Laboratory.

Dentz, Jordan. 2011. *Building America Expert Meeting Report: Hydronic Heating in Multifamily Buildings.* Washington DC: DOE Building Technologies Program.

Dentz, Jordan; Ansanelli, Eric; Varshney, Kapil PhD, PE. 2015. *Energy Efficient Controls for Multifamily Domestic Hot Water Systems.* Albany, NY: NYSERDA.

DOE. 2001. *Pump Life Cycle Costs: A Guide to LCC Analysis for Pumping Systems.* Washington, DC: Office of Industrial Technologies.

DOE. 2002. *United States Industrial Electric Motor Systems Market Opportunity Assessment.* Burlington, Mass.: OFFICE OF ENERGY EFFICIENCY AND RENEWABLE ENERGY.

Enovative. 2008. *Case Study - Oxford Club Apartments.* Case Study, Venice CA: Enovativegroup.com.

Grundfos. 2017. "High Performance Circulators." *California Technical Forum.* California Technical Forum. 27.

IECC. 2015. "2015 International Energy Conservation Code."

Khattar, Mukesh, and Ankit Somani. 2010. *Energy-Efficiency with Domestic Water Heating in Commercial Buildings.* ACEEE Summer Study.

Klein, Gary, and Larry Acker. 2006. *Benefits of Demand-Controlled Pumping.* Home Energy.

NEEA. 2014. *2014 Commercial Building Stock Assessment: Final Report.* Portland, Oregon: NEEA.

—. 2018. *Extended Motor Products Initiative.* https://neea.org/our-work/programs/xmp.

—. 2018. *Residential Building Stock Assessment 2; Multifamily Building Report.* https://neea.org/img/uploads/Multifamily-Web-Version.pdf.

—. 2018. *Residential Building Stock Assessment 2; Single-Family Homes Report.* https://neea.org/img/uploads/Single-Family-Web-Version.pdf.

Rogers, Ethan A. 2014. *Development of a New Extended Motor Product Label for Inclusion in Energy Efficiency Programs.* ACEEE.

RTF. 2016. *Research Strategy for Efficient Pumps, December 6, 2016.* Research Plan, Portland: Regional Technical Forum.

Schoenbauer, Ben, Merry Sweeney, and Alejandro Baez Guada. 2018. *Evaluation of New DHW System Controls in Hospitality and Commercial Buildings.* Minneapolis: MN Center for Energy and Environment.

Tingleff, Bob, Sarah Widder, and Adam Hadley. 2017. "Regional Technical Forum Presentation, Efficient Circulator Pumps & Controls." Portland, March 21.

US DOE. 2015. *Technical Support Document: Energy Efficiency Program for Consumer Products and Commercial and Industrial Equipment.* Washington DC: Office of Energy Efficiency and Renewable Energy.

Zhang, Yanda PhD. 2013. *Multifamily Central Domestic Hot Water Distribution.* California Energy Commission.

9 Appendices

9.1 Data Submission Form

Data Submission Form.xlsm

9.2 Data Management Plan

Data Management Plan, Data Collection and Quality Control Process

This document serves as a guide to data collection, quality control, data management, and data extrapolation for the XMP Pump Research. These steps were followed to ensure quality and transparency in the treatment and analysis of the project data. The table below shows the different roles referred to throughout this document and the definition and responsibilities of each role.

Table 90: Data Management Roles and Role Responsabilities

Role	Definition
Prospect	Prospective data contributor
Data Contributor	A prospect who has access to relevant data and agrees to participate
Striker	Individual team member assigned to establish initial contact with a prospect and determine if the prospect is interested in participating and has suitable data. The striker is also responsible to transition the relationship to the data manager, once a prospect agrees to participate
Data Manager	Data manager responsible for making sure the data received is complete and applicable
Database Manager	Database manager responsible for uploading, organizing, and analyzing the data within the database.
Contract Administrator	The individual with access to the project DocuSign account who sends NDAs and Participation Agreements for signature

The XMP Pump Research involves collecting two different types of data: **Audit Data** and **Operational Data**. Audit data consists of the information on the pump and the system on which the pump is installed. This includes information like pump manufacturer and model number, application, load control method, pump material, etc. This is static information, or information that characterizes the specific pump and won't change unless system/installation changes are made. Operational data is data logged at discrete (and usually consistent) intervals[69] that show how the pump operates over time. Operational data can

[69] Operational data can also be formatted with "change of measurement" intervals, where the operational data and time of measurement is logged when the variable changes value.

consist of logged water flow, pump power consumption, pump speed, and operational state changes (on/off).

Collecting audit and operational data takes two forms in this research: **Existing Data Collection** and **Primary Data Collection**. Existing data collection is the procurement of data that was collected by systems or personnel not on the research team. This includes audit and operational data collected through custom utility incentive programs, building automation systems, direct digital control systems, or any other form of pump monitoring and data logging that a data contributor utilizes. Primary data collection involves a member of the research team working with the data contributor to identify, log, and collect the audit and operational data. The research team's level of involvement can vary from minimal—taking one spot measurement of an operational variable or simply supporting the data contributor through submitting data—to deeply involved, such as identifying the pumps, completing the audit data collection, connecting data measurement and logging equipment, replacing pumps, and removal of equipment.

The following sections outline the data collection steps for both existing data and primary data collection. The process of collecting and ensuring quality control is different between the collection methods, but the same analysis methodology will be used.

1. Existing Data Collection Steps:

1.1 Before Data is Submitted

1. The team developed a comprehensive list that includes prospective data contributors' relevant company and contact information (prospect) and assigned a striker for each one. The striker is the person assigned to establish initial contact and determines if the prospect a) is open to participating in XMP and b) has data that matches the research plan requirements
2. The striker may choose the form of communication for initial contact with a prospect (phone call, email, etc.) Each striker will have an individual outreach tracker that he or she must keep updated and send to the data manager the day before the weekly meeting. An outreach tracker is a spreadsheet where contact details, such as date and type of contact and response are recorded. The information in the individual outreach trackers roll up to a master tracking document.
3. The manager will update the master tracking document and highlight any issues to be discussed at the meeting.
4. Strikers will follow up and maintain contact until the prospect a) commits to having data and is willing to participate or 2) confirms that the data is not relevant, or the prospect does not wish to participate. The striker will log this information in their tracker.
5. Once a prospect agrees to move forward, the striker will transition the relationship to the data manager by setting up a meeting between him or herself, the prospect and the data manager to make introductions. This is a soft handoff and may require continued participation from the striker until the participant is comfortable.
6. The striker and manager will discuss the level of data compensation available before meeting with prospect.
7. The introductory meeting will be held between the striker, prospect and data manager to orient the prospect on:

a. The type of data we would like to collect
b. Data requirements
c. Specific time intervals and timeframe
d. Anonymity and data security
e. Data storage and transfer
f. Non-disclosure agreement (NDA)
g. Data stipend

8. Once the meeting is completed and the prospect has agreed to submit data, the prospect becomes a data contributor and is tracked as such in the master tracker.
9. If the contributor, or contributor's company officers require an NDA, the manager will ask the contributor for the name of the person within their company who has authority to sign an NDA and request related information, including:
    a. Organization's legal name
    b. Address
    c. Signer's name
    d. Signer's title
    e. Signer's email
    f. Signer's phone number
10. The data manager will send this information to the contract administrator, who will facilitate the DocuSign process to get the NDA signed electronically by both parties (data contributor and NEEA). If the company signer prefers, a hard copy of the NDA may be signed, scanned and sent to the contract administrator.
11. Either the data manager or the striker will email the data collection tool to the participant. The data collection tool is an Excel spreadsheet that outlines the required and optional data that is being collected, and provides cells that the information can be entered into. It also includes instructions for how to add the data. This email will include instructions for how to securely submit the completed tool and any other relevant files. If the data is subject to an NDA, emphasis will be included in the email that data should be submitted through the secure pathway and not via email.
12. The manager will set a weekly calendar reminder from the day the tool is provided, to follow up with the contributor until the data has been submitted.
13. The first weekly follow-up will be via telephone, if possible and include a discussion to:
    a. Answer any questions the contributor might have
    b. Emphasize data security and use of a secure data submission pathway
14. If the contributor does not respond to the manager's outreach after the data collection tool is sent, the striker will re-establish contact with the contributor to determine if there is a problem with the instructions and to resolve any other issues the contributor may be encountering.

1.2 After Data is Submitted

1. An automatic notification will be received by the data manager that a file has been uploaded to Sharefile. The data manager will mark the corresponding contributor as "data submitted" in the tracker.
    a. If the data is not submitted through the Sharefile secure file transfer process but is emailed to the data manager, the data manager will transfer the files to the secure folder on Sharefile and delete the email.

2. The data manager will create a subfolder within the secure folder and label it with the name of the organization. The submitted data will be moved to this folder and saved.
3. The data manager will send a notification email within 24 hours to the database manager that data has arrived, once the data is received and filed.
4. The data manager will email the database manager to notify them that the audit data QA/QC is complete. This email will include:
   a. Row number(s) in which the pump data is located within the Existing Data Collection Log
   b. Confirmation that QA/QC has been completed; and
      i. Confirmation that the relevant data submission form is linked in the Existing Data Collection Log and a link to the associated QA/QC form.
5. If the data manager must extend the time to complete the QA/QC, then he will email the database manager to explain the need for an extension and the two will mutually agree on a new QA/QC deadline.

The initial QA/QC Steps that are taken before transfer to the database manager are included in the section "QA/QC" below.

2. Audit Data QA/QC Steps

1. The data manager, or assigned support staff, will open the submitted files and review the information that was collected. This high-level review is to ensure the data that was submitted aligns with what was discussed with the contributor.
2. If support staff is performing the audit data QA/QC the data manager will review the QA/QC performed to make sure it was accurately reviewed. In the following section "Data Manager" refers to the person performing the QA/QC.
3. If, on first review, the data that was submitted does not match what was discussed between the data manager and the data contributor the Data Manager will email the data contributor to set up a time to discuss and resolve the discrepancy.
4. If the data seems to match what was discussed with the data contributor, then the Data Manager will close the file and create a subfolder within the organization folder that will be labeled with the pump identifier provided by the data contributor (and the site identifier if there are multiple sites submitted by the data contributor). If there are not multiple sites, there may not be a site identifier. If information was submitted for more than one pump, multiple subfolders will be created with each file named for the pump identifier. If no pump identifier is given and there was only one pump submitted, then the identifier "Pump 1" will be used. If there are no pump identifiers provided and there is more than one pump submission, then:
   a. If it is evident what audit data corresponds to the operational file (by the two data types being submitted in the same file or other methods) the folders will be labeled with "Pump {number}", with number starting at 1 and increasing sequentially.
   b. If it is not evident what audit data corresponds to the operational file, then the Data Manager will reach out to the data contributor to determine what the pump identifier is for each pump for which data has been submitted.
5. The Data Manager will determine if the data was submitted using the most current data submission form. If the data is not submitted in the most current version of the data submission form, then of the data will be copied into the most current data submission form and saved in the folder labelled with

the data contributor's pump identifier. This data submission form will be saved using the naming convention:

"DataSubmissionForm_{DataContributorName}_{SiteName}_{ContributorPumpIdentifier}_NEW"

6. A copy of the QA/QC checklist will be saved in the folder labelled with the data contributor's pump identifier. The naming convention for the QA/QC document will be:

   "QAQC_{DataContributorName}_{SiteName}_{ContributorPumpIdentifier}"

7. Once the information that was provided by the contributor is in the most current data submission form, the form will be reviewed to ensure all the necessary audit data is included. This review will include:
   a. Ensuring all data contributor information is included
      1. Contributor Name, Company, Industry Description, and a contact email for follow-up
   c. Ensuring the industry description matches the application and sector selected
   d. Ensuring pump type is designated (Efficient C&I Pumps or Circulators) and that only information for the designated pump type is included. If there are data in cells that are listed for the non-selected pump, then the Data Manager will reach back out to the data contributor for clarification on what that information represents.
   e. Confirming the ZIP code and General Information section is complete.
      1. Ensuring that all cells that are left blank or have "unknown/other" listed must have notes included.
      2. Ensuring there are not units in the following cells (must be numbers only)
         a. Motor Horsepower
         b. Pump Horsepower
         c. Volts
         d. Amps
         e. Impeller Diameter
         f. Pump head
         g. Speed
         h. Estimated Age
   f. Confirming all units are listed and the value provided is a reasonable value for the listed units.

2.1 For Efficient C&I Pumps

a. Ensuring the sector chosen corresponds with the industry listed in the Data Contributor Information and the application
b. Ensuring the pump class selected is the same consistent with previous discussions between the data manager and data contributor.
c. Using the Manufacturer's website and the provided model number to check that the chosen pump class is accurate.
   Note: A screenshot of either the pump from the website, the information that determines the pump class, or a picture of the installed pump will be included on the literature value page of the data submission form to ensure the correct pump class is selected
d. Ensuring that, if "Other" is selected for load control method, notes are included
e. Ensuring that, if "Other" is selected for the pump redundancy role, notes are included
f. Confirming that the pump class is compatible with multi-stage configuration, if more than one stage is indicated
g. Ensuring "Number of Stages" is listed as a whole number, with no units or decimals
h. Reaching back out to the data contributor for clarification, if any of the following items are not met:

2.2 For Circulators

i. Make sure the sector chosen corresponds with the industry listed in the data contributor information section and the application
j. Ensure the “Circulator System Type” is selected and is consistent with the system type that was discussed with the data contributor
k. Ensure the “Circulator Type” and “Motor Type” are selected and make sure they correspond with the model information provided
l. Confirm the pump function corresponds to the system type. If “Other” is selected, notes must be included
m. If any information is not provided or is listed as “Unknown” but can be determined through manufacturer information, then enter the information into the data submission form and confirm through follow-up with the data contributor. If the sections listed as “Unknown” and is not able to be determined through manufacturer information, then follow-up with the data contributor to fill in the missing information

2.3 For Optional Efficient C&I Data

n. If a manufacturing date is not listed but an estimated age is known, enter “1/1/{Year that the pump was installed}” and note in the notes column that the pump was installed in the listed year
o. If “Other” is listed for enclosure type, there must be a note indicating the type of enclosure
p. If the pump is a variable speed control pump then “Drive Installation Method“ cannot be listed as “No Drive Attached” (verify this is not the case)

2.4 For Operational Circulator

q. Make sure it is noted which information is not included and follow up with the data contributor to determine if the information is not known, or was just not completed and left blank

2.5 Literature Values

r. If the pump curve is provided, confirm that the pump curve matches the manufacturer, model number, impeller diameter, and horsepower. If it does not, the data manager should find the pump curve they believe to match the pump submitted and follow up with the data contributor on this topic
s. If the pump curve is not provided, then the data manager will contact the manufacturer through their website or technical support chain to retrieve the pump curve.
t. Using information on the pump curve or from information submitted by the data contributor log the following information on the “Literature Values” tab in the corresponding columns:
u. Nominal Speed of the pump. Pump nominal speed is listed in Table 91

Table 91: Pump Nominal Speeds

Nominal Speed (RPM)	Actual Pump Speed Range (RPM)
1800	1,440 – 2,160
3600	2,880 – 4,320

v. Rated Impeller Diameter, which is the diameter listed on the pump curve
w. Runout, which is the flow at which the pump curve ends
x. Flow at Best Efficiency Point (BEP)
y. Head at BEP

z. For 6 different points on the head/flow curve where efficiency is known, the following values will be found
    i. Flow (gpm)
    ii. Pump curve head (ft)
    iii. Efficiency (%)
i. Using these values, determine the following:
    i. A line-of-best fit curve for the head vs. flow chart (the pump curve). The highest polynomial that can be fit, without a slope reversal, up to 6th order, will be chosen.
    ii. The 2nd order polynomial coefficients for the efficiency curve

8. Following the finding of the values from literature, a link to the data submission form will be added to the Operational Data Tracking Log file and the database manager will be notified that the audit data may be uploaded to the database.
9. If the QA/QC process for the audit data is projected to take longer than the allotted 3 days, the Data Manager will send an email to the database manager to provide notification of the delay.

3. Operational Data QA/QC

1. Either after the first-check of the audit data is completed, or while waiting for the data contributor to contact the data manager regarding missing/incomplete information, a primary check of the operational data must be completed. This check will occur when the data is in the format in which it was submitted (whether copied into the data submission form or in a separate file). This initial check includes:
    a. Reviewing the time range of the submitted data to understand the date range of information submitted. This allows us to make sure the needed amount of operational data is submitted.
    b. Reviewing the measured information of the submitted data to understand what type of data is included (power measurements, flow measurements, speed measurements, etc.) ensuring at least 2 of the 4 required data points are included in the operational data.
    Note: If multiple pumps are included in one data set, then the data submission form will be filled out for each pump, and the column will be labeled with a unique identifier

Unique Identifier: The unique pump identifier is designated by the database manager and references the submission number and pump within a specific organization's data. For example, if a specific pump is submitted by the 5th organization to submit information and is 3 of 3 pumps included in the submission, then the unique identifier for the pump will be: Site ID 5 Pump ID 15, with Pump ID being unique to that pump—that is, three pumps will have Site ID 5, but **only one** pump can have the Pump ID 15. This identifier will be attributed to the pump after the primary check of the operation data during the QA/QC process. This will allow for a comparison to be made between pumps submitted by the same organization to ensure patterns attributed to regional operating norms are not simply functions of the organization operating the pump but are indeed characteristic of pumps in the region.

2. Once a preliminary check of the operational data is complete, the data will be formatted to be processed in the database. At this step, the formatting only involves standardizing the location and format of the data. It does not include any calculations or unit conversions.

3.1 Raw Operational Data Standard Formatting

3.1.3 Entering Operational Data into Data Submission Form

1. The Raw operational data will be copied onto the "Copy and Pasted Data (Optional)" tab of the pump's data submission form.

2. This tab will have 24 columns, which will include (starting at Column A and progressing alphabetically from there) the following columns, labeled:
    a. "Time Stamp"
    b. "Flow"
    c. "Flow_Units"
    d. "Speed"
    e. "Speed_Units"
    f. "Power"
    g. "Power_Units"
    h. "Differential_Pressure"
    i. "Differential_Pressure_Units"
    j. "Temperature"
    k. "Temperature_Units"
    l. "State Data (1=on, 0=off)"
    m. "Measured Data Instance"
    n. "Weather dependent (0=no, 1=yes)"
    o. "C_Flow"
    p. "C_Flow_Units"
    q. "C_Speed"
    r. "C_Speed_Units"
    s. "C_Power"
    t. "C_Power_Units"
    u. "C_Differential_Pressure"
    v. "C_Differential_Pressure_Units"
    w. "C_Temperature"
    x. "C_Temperature_Units"
3. The timestamp that the data was submitted in will be inserted in Column A, and the values for each variable submitted will be entered into the column corresponding to that variable, in columns B through N. Only the value submitted will be included in the variable column.
4. The unit corresponding to each submitted variable will be entered into the column labeled with the corresponding "Variable_Units" in columns B through N.
    e.g., if the data contributor sends logged interval data that includes Hz, then the values associated with this variable would be entered into column D, "Speed", and the unit Hz would be entered into column E, "Speed_Units"
5. The data in columns A through N, or all data in columns that do not begin with "C_" are considered Raw Operational Data and will be uploaded to the Raw Operational Table in the Database
6. The Data Manager will start the process of standardizing the units and calculating the values for operational variables not provided.

3.1.2 Weather Data

To control for the effect of weather on pump operation the team normalized annual pump operation to reflect operation during a typical meteorological year. The team acquired actual and typical meteorological year weather data for a 30-year period (also known as normalized weather or TMY3 weather) from National Oceanic and Atmospheric Administration (NOAA) weather stations.

While some pumps were submitted with outdoor air temperature data the research team decided to use NOAA weather data for all the pumps, ensuring consistency between pumps. If a pump was submitted with outdoor air temperature the team replaced it with NOAA weather data.

Data contributors included the zip code where a pump are located in the submission form. The research team used this zip code to map the pump location to a weather station. The team used the Haversine Formula to calculate the distance between two locations[70].

The team used actual weather data to model pump usage and to quantify the effect of weather on pump consumption and then used normal weather data to adjust operational data to reflect a typical meteorological year.

To control for weather data completeness, weather stations missing data for more than 2% of the time were not used. The research team applied two methods to address missing data points in weather data:

a. If the distance between two values is less than or equal to one hour the last registered observation is used
b. If missing data spans more than one hour, the team used 24-hour lagged observation to replace the missing value

3.1.3 Standardizing Raw Operational Data

1. Once the Raw operational Data is in the Data Submission Form it will be standardized to consistent units, and calculations will be performed to determine the other variables needed for the analysis. The standardized units for each variable are as follows:
    a. Flow – gallons per minute, or gpm
    b. Speed – Revolutions per minute, or RPM
    c. Power – Kilowatts, or kW
    d. Differential Pressure – Feet of Head, or ft
    e. Temperature – Fahrenheit, or F
2. If the Flow or Power are provided at the system level, with one measurement representing the value for multiple pumps in the system, this will be noted, communicated to the database manager, and the distribution to specific pumps will be performed in R.
3. If the Flow or Power are provided as a "running total" or a "cumulative value" (e.g., a running total of gallons to pass through the pump) then this will be noted, communicated to the database manager, and these values will be converted to a rate ({unit of measure} per {unit of time}) and standardized in R.
4. The unit conversions for each variable will be tracked in the Operational Data Tracker by the data manager, who will enter the equations into the data submission form. The calculated values and standardized units will be in the column that corresponds with the variable and variable unit, but that begins with "C_" (columns O through X).
5. The calculations that are performed on any data to determine the values for variables not provided will be performed by the data manager and logged into the operational data tracker by the data manager.
6. If any data are submitted with the standardized unit listed above, the data and the units will be copied into the corresponding columns that begins with "C_", and no calculations will be performed on it.
7. The initial QA/QC Report will be developed for the raw operational data and the standardized operational data

[70] The Haversine formula deterimes the great-circle sidtance between two points on a sphere, which allows the team to accurately calculate the distance between two points on the globe. The research team assumed the earth was perfectly spherical for this calculation.

3.1.4 *Raw and Standardized Raw Operational Data QA/QC Report*

1. Once the data manager notifies the database manager that operational data is ready, the database manager will generate a QA/QC report to share with the data manager within 24 hours. The QA/QC report will include:
   a. The file path to the pump-specific data submission forms
   b. The data contributor, the site within the data contributor (if applicable), and the contributor specific pump ID
   c. The operational data time period, which includes the start date, the end date, and the number of days the data spans
   d. The number of data instances that occur at each time interval, with the interval rounded to the nearest 5 minutes
   e. All operational variables and the units the units in which they were provided
      i. This includes the percent of the data instances that have a value for each operational variable
   f. The number of missing data points
   g. The operational data summary statistics, which will be repeated for both the raw operational data and the standardized raw operational data. This includes:
      i. The minimum value
      ii. The Maximum value
      iii. The 1st Quartile
      iv. The Median
      v. The Mode
      vi. The 3rd Quartile
      vii. The upper and lower fences
      viii. Time series plots for each operational variable. The operational variables may include any of the following:
      ix. Time Stamp
      x. Flow
      xi. Speed
      xii. Power
      xiii. Differential Pressure
      xiv. Operational State Data
      xv. Temperature
2. A pressure vs flow graph will be plotted for the standardized raw operational data
3. The operational data QA/QC reports will be reviewed by the data manager to ensure there are no issues with the operational data, these issues can include but are not limited to:
   a. There are no negative values.
   b. The ranges of operational data values correspond to the units provided
   c. Any values that are above or below the upper and lower fences are present in multiple variables
4. If the data range is not within the realm of possibility, the data manager will get in touch with the pump owner to verify the data and get more information. If an issue is seen with the data by the data manager a discussion will be had on the issue and it will be determined if the issue is a function of the display of the data, the treatment of the data, or if it is an anomaly that will be adjusted for. Any changes or cleaning of the data that occurs at this point will be logged in the operational data tracking log.

3.1.5 Operational Data Time Stamp Aggregation

After the QA/QC report of the raw and standardized raw operational data is reviewed, the standardized raw data will be aggregated to hourly instances. During raw operational data standardization, the raw data submitted by the data contributors will be converted to hourly instance data. This is to reduce the number of instances to a manageable amount and standardize the interval length across all pumps.

This process aggregates instances that are more granular than 1 hr into 1-hr intervals, and calculates a time-average value for each variable listed in the "C_" columns of the data submission form.

1. Operation data sometimes comes with duplicated timestamps. In those duplicated timestamps, there are instances where one operational variable is registered to the first duplicated timestamp and another operational variable is registered to the second duplicated time stamp. To not lose any information by deleting duplicate rows, the team takes an average of operational variables belonging to the duplicated time stamps and stores a single record per unique time stamp before starting the aggregation process.
2. The date range of operational data is determined for the variables submitted. This is the date of the oldest instance submitted to the date of the newest instance.
3. Using this range, a time series is created, starting at the hour before the oldest submitted data instance, proceeding at hourly intervals, and ending at the hour after the newest instance is submitted.
    a. For example: If the operational data starts from 2017-09-01 12:37:00 and ends at 2017-11-12 19:20:00, hourly instances are artificially created from 2017-09-01 12:00:00 to 2017-11-12 20:00:00
4. This time series is then inserted into the raw data time series, adding time stamps to the time series if the hourly value is not present—but not duplicating the instance if the raw data includes an instance occurring on the hour.
5. The time interval between each instance in the original raw time series is calculated. If any of the time intervals are greater than 1 hour, any added hourly time stamps that fall within that hour are removed.
6. For the added hourly time stamps that remain, the most recent previous value for each variable is used as representative of the value during the added time stamp.
7. The hourly time-weighted average value for each variable is then calculated for each hourly time stamp.
8. These values are stored in the XMP Database. This data will be either interpolated or extrapolated, depending on the length of time between each time stamp, to represent 8760 hrs of data, or one year of operational instance data.

If the raw operational data is provided by the data contributor in cumulative value, not a rate (e.g., gallons instead of gallon per minute), the data will first be converted to rate data, and then the process of time stamp aggregation will be followed. To convert cumulative data to rate data:

a. Calculate the change in variable value between each time stamp.
b. Calculate the time interval between each record and store it as minute data.
c. Divide change in variable value by the minutes between each stamp to find the per minute rate.
d. Convert flow and power to the standardized units which are GPM and kW respectively.

If the flow or power that are submitted by the data contributor are system level values, then the values need to be distributed to each pump in the system.

Flow Distribution: The Speed of each pump in the system is combined, and the percent of the total speed each pump is operating at is used as a weighting factor to distribute the flow to each pump. For example: If 3 pumps are operating on a system, with 100 gpm flowing through the system and all three pumps operating at 1800 RPM, then each pump has 33.33 gallons flowing through it.

Power Distribution: Power is distributed using the flow with the understanding that power is proportional to the cube of flow.

9. A QA/QC Report that follows the same format as the initial report will be created for the aggregated operational data. This report will be reviewed by the database manager and data manager to ensure no issues were created in the aggregation process.
10. The next step in data management is the Data Annualization Process, outlined in Section 4.2.4 of XMP Savings Validation Research on Clean Water Pumps and Circulators Research Report.

9.3 Database User Guide

The XMP Pumps Database accompanies this report and contains all of the raw and annualized audit and operational data collected throughout the source of the study.

The database contains two separate data-storage methods: Tables and Views. A Table is a permanent location within the database. Information is uploaded to the database and stored in Tables. A View is a way to display information from multiple tables in one place. Calculations can be run on data stored in tables and the values from the calculation used to populate a View.

Information, in both Tables and Views, are sorted using Schema. Schema are naming conventions that allow Tables and Views to be classified based on the type of information that is stored in it. In the XMP Pumps Database the Schema are determined by the text in name of a table or view that precedes the first period. For example, a Table in the Database is named "AUDT.EfficientC&I". This table is part of the "AUDT" Schema, and stores the Efficient C&I Pump Audit Information. Listed below are the Schema used in the database.

Schema	**Description of Schema**
AUDT	Holds Audit Data from submitted Clean Water Pumps (referred to in the database and "Efficient C&I Pumps") and Circulators
CALC	Holds calculations performed using the Audit Data; all calculated values store in this table are calculated in R
dbo	Holds Raw data uploaded from the data submission forms, before it is stored in AUDT, LIT, NOTES, or OPS
LIT	Holds the Literature Values for the submitted pumps (e.g., flow at BEP, runout, etc.)
LOOKUPS	Holds look-up tables used in calculations
MSTR	Holds the key, listing the Site ID and Pump ID for all pumps in the database
NOTES	Holds the notes submitted with the audit data for Circulators and Clean Water Pumps
OPS	Holds the Operational Data for submitted Clean Water Pumps and Circulators
REF	Holds reference information
XMP_AUDT	Holds the finalized Audit Data, for publication
XMP_CALC	Holds the finalized calculated data, for publication
XMP_LIT	Holds the finalized Literature Data, for publication
XMP_LOOKUPS	Holds the finalized Literature Data, for publication
XMP_NOTES	Holds the finalized Notes submitted with the Audit Data, for publication
XMP_OPS	Holds the finalized Operational Data, submitted and annualized, for publication.