PUMP EFFICIENCY MONITORING - GIVING UP THE CARBS

Paul Winstanly (Wellington Water)
James Curtis (Cardno)
Brett Eaton (Cardno)

ABSTRACT

Electric motors use 10% of the world's energy with one in four electric motors installed on pumps. Electricity accounts for over a quarter of direct greenhouse gas (GHG) emissions caused by human activity (Grundfos, 2012).

Many pumps run at efficiencies lower than their newly manufactured states and outside of their peak efficiency. This results in wasted electricity and resources, increased carbon emissions, loss of capacity and while pump efficiency improvement costs are typically much less than the cost savings from the efficiency gains (The Economist, 2021).

Monitoring the potential for functional failure from efficiency deterioration allows water utilities to proactively intervene with pump refurbishment or renewal (ensuring that the most efficient pump is selected) and operational efficiency improvements which provide budget cost savings with a less than a three-month payback period and risk mitigation for critical assets.

This paper discusses the criteria for efficiency monitoring, the conventional and advanced thermodynamic techniques employed and the various key performance indicators (KPIs) that are used to validate decisions for pump maintenance and operational improvements.

KEYWORDS

Pumping, energy efficiency, continuous monitoring, condition based maintenance, performance benchmarking, thermodynamic method, carbon emissions, budget cost savings, risk mitigation intervention, vibration monitoring, critical assets

PRESENTER PROFILE

Paul Winstanley trained as an electrical engineer and has been working with water utilities for over 22 years. His current role is with Wellington Water as a Utilities Planning engineer. Paul has a key role in managing asset reliability to reduce costs, carbon emissions and operational risk.

James Curtis has over 11 years' experience as a mechanical engineer working on the design and manufacture of water & wastewater and industrial processing plants, machines and equipment. At Cardno James leads their pump performance monitoring services and prepares designs for various water & wastewater infrastructure projects.

1 INTRODUCTION

Cardno and their technology partner Robertson Technology (based in Perth, WA) have been helping to realise efficiency gains via pump efficiency monitoring on pumping systems operated by Wellington Water, Watercare, Hamilton City Council, Tauranga City Council, Western Bay of Plenty District Council, Kapiti Coast District Council, Water Corporation, Sunwater, Seqwater and Goldenfields Water Authority among others.

The fundamental purpose of maintenance is to contribute to the production and profit (cost savings) objectives of the organisation by keeping plant reliability at the optimum level. The key performance indicator (KPI) for maintenance is the extent of available production capacity related to the costs, otherwise known as efficiency.

Condition based maintenance for a pump is when maintenance is carried out based on evidence that it is necessary such as deterioration in efficiency and/or increased noise and vibration. The UK department of trade and industry found that the cost savings from condition based maintenance are 10 to 20 times the cost of implementation (Beebe, 2004).

The benefits of condition based maintenance for pumps include:

- Electricity cost savings from scheduling overhaul to restore lost performance at the optimum time and operational efficiency improvements
- Forecasted maintenance which ensures accurate decisions are made
- Improve productivity by avoiding unplanned plant shutdowns which disrupt water services to households and tie up limited resources
- Enable deferred renewals
- Early detection of pump damage to provide risk mitigation on critical assets
- Improve the quality of water services, customer relations, plant design and the efficiency of the organisation
- Provides accurate pumping system performance information used for validating upgrade design, network investigations, planning and modelling rather than relying on available data such as design reports which often do not reflect operational reality

Wellington Water have been implementing Thermodynamic efficiency monitoring using the Robertson Technology system for 11 years and found that the payback period was less than three months on their 34 bulk water pumps from the electricity cost savings alone.

Field testing and reports (completed by Cardno) cost $36k per year based on an average testing frequency of 3.2 years.

8% electricity savings were realised on their electricity bill of $2.5M per year so the electricity cost savings were $200k per year.

2 DISCUSSION

1 PUMP EFFICIENCY

Efficiency deteriorates due to internal wear or system changes and is effectively masked by variable speed drives (VSD's) which ramp up to meet target flow/pressure set points such that there are many pumps that are not operating as efficiently as they should.

Efficiency deterioration is a function pump size, liquid pumped, pump design, materials of construction, pump selection, run hours and operating efficiency therefore not all pumps should be maintained at the same frequency.

To provide the fastest payback period it is recommended that pumps with highest energy use and/or criticality including age and/or known performance issues should be prioritised for efficiency monitoring. Monitoring efficiency becomes more important as the pump ages in operation due to increasing potential for critical failure.

Efficiency is the ratio of the level of service or work done by the pump to the amount of electricity it consumes.

$$Efficiency = (volume\ pumped \times total\ dynamic\ head \times density \times acceration\ of\ gravity) \div electricty\ consumption$$

Volume pumped is in cubic meters, total dynamic head is in meters, density is the density of water in kilograms per cubic meter and electricity consumption is in watts.

Total dynamic head is the total head produced by the pump and should consider the pump suction pressure, discharge pressure, the static height difference between the pressure measurements relative to the pump, the velocity head loss in the pump, pipe and fitting losses e.g. valves between the pressure measurements.

$$Total\ dynamic\ head = discharge\ pressure - suction\ pressure - static\ height\ difference - velocity\ head - fitting\ loss$$

$$Velocity\ head = velocity^2 \div (2\ x\ acceration\ of\ gravity)$$

$$Fitting\ loss = velocity\ head\ x\ k$$

Velocity is in meters per second and is the velocity of the liquid in the pipe which is calculated from the flowrate and pipe diameter. The friction k factor is based on the type and number of pipe fittings.

2 METHODS OF PUMP EFFICIENCY MONITORING

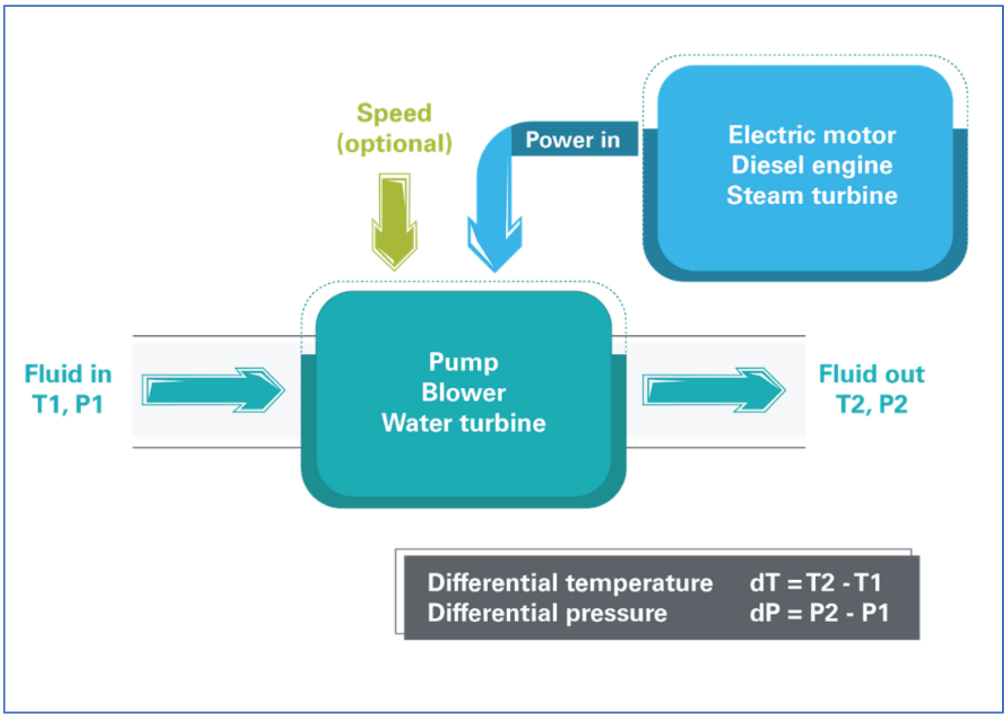
2.1 THERMODYNAMIC METHOD

Precision class Thermodynamic measurement is covered by ISO 5198 and calculates efficiency from changes in enthalpy (energy per unit mass) of the liquid being pumped via suction and discharge temperature and pressure measurements. The Robertson Technology system has calibrated accuracy and repeatability to +/-0.5%.

The system calculates the flowrate, without the need for a conventional flow meter, from the efficiency, pressure and motor power measurements.

A schematic of the Thermodynamic measurement system is shown in Figure 1.

Figure 1: Thermodynamic measurement system



For multiple pumps operating in parallel, pump efficiency and flowrate are able to be measured simultaneously for individual pumps using the Thermodynamic method.

The thermodynamic method is used for water, wastewater and stormwater pumps that are dry mounted or installed in a wet well. For bore water pumps the thermodynamic method can't be used as it's not possible to measure the pump suction liquid temperature.

Field testing aims to cover the full operating range/pump curve via. valve throttling or by varying the VSD speed (then the data is adjusted using the pump affinity laws) to obtain measured head, power and efficiency vs. flow curves to compare to the manufacturer's curves to provide an assessment of the pump performance. This analysis also highlights what the best VSD speed range is to ensure that the pump is operating at its best possible efficiency.

Figure 2 and Figure 3 show typical efficiency and head vs. flow curves from field testing, demonstrating efficiency and capacity loss due to internal wear.

Figure 2: Flow v.s. Efficiency Curve

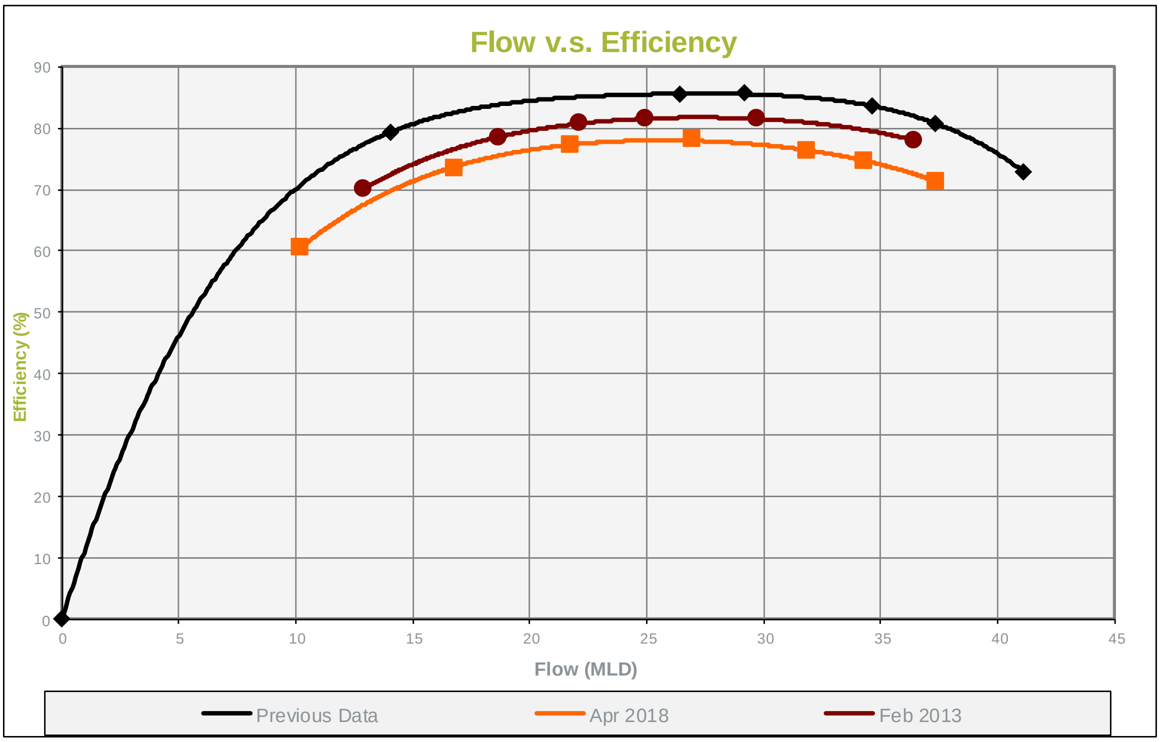
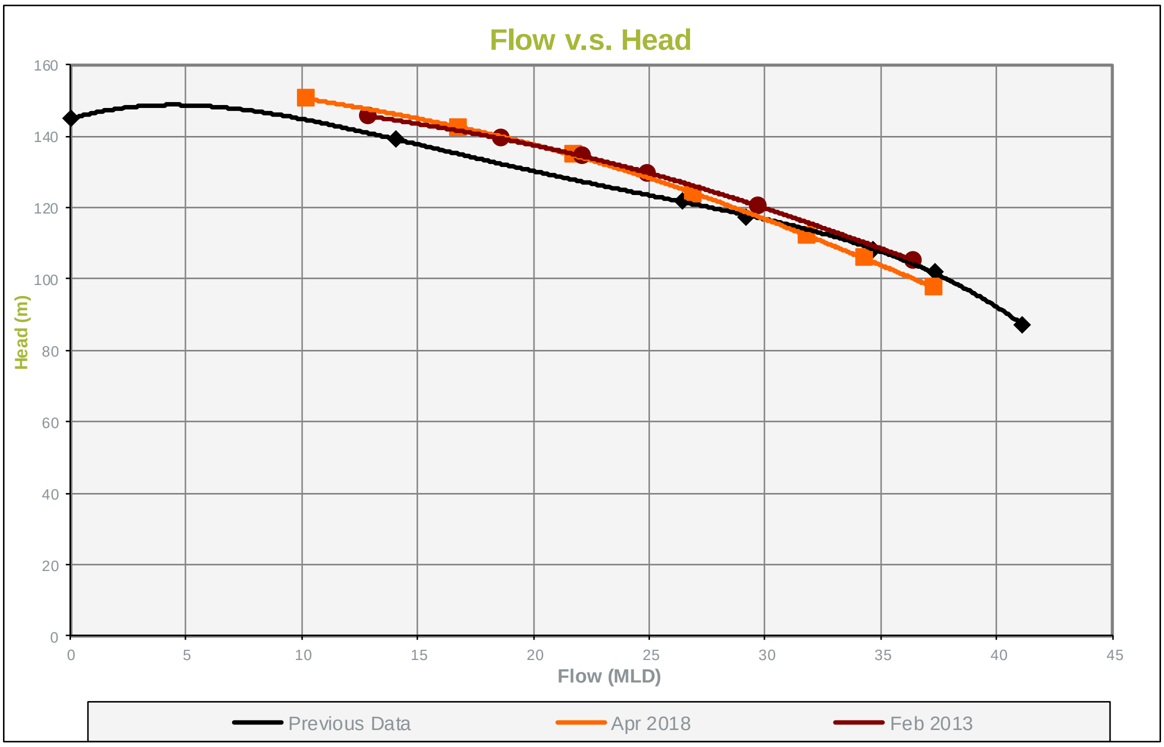


Figure 3: Flow v.s. Head Curve



Robertson Technology have supplied thermodynamic pump testing equipment to 23 countries where it has been proven in thousands of pump tests, under widely varying conditions.

Robertson Technology's specification for differential temperature measurement is a long-term calibration accuracy of < 0.001 °C for 10 years which permits accurate efficiency measurement for total dynamic heads of 5 to 10 m and above. Each temperature probe comes with two temperature sensors, operating independently and an alert is provided in the event of any significant discrepancy between the two sensors.

2.2 CONVENTIONAL METHOD

The conventional method to calculate efficiency is from flowrate, pressure and motor power measurements. The flowrate is typically measured using an existing pump station flow meter or using volumetric measurements in the suction or discharge well or tank.

For multiple pumps operating in parallel, pump efficiency and flowrate can't be measured simultaneously for individual pumps as the pump station flow meters are typically installed on the common rising main rather than on individual pump discharge pipes.

The accuracy with which efficiency can be calculated by the conventional method depends on the accuracy of the flowrate and electrical power meters and pressure sensors. Many existing pump station flow meters are understood to have errors due to a number of factors including age, incorrect installation, fouling inside pipes and sensor drift over time.

Thus, errors in the calculation of efficiency using the conventional method will possibly be too high for accurate calculation of the electricity cost savings and validating decisions for operational efficiency improvements. An indication of the scale of this problem is found from the large amount of data filtering and assumptions that were required in the Water Services Association of Australia (WSAA) (Livingston et al., 2015) and Water Research Foundation (WRF) (Badruzzaman et al., 2017) pump efficiency monitoring programmes which employed the conventional method.

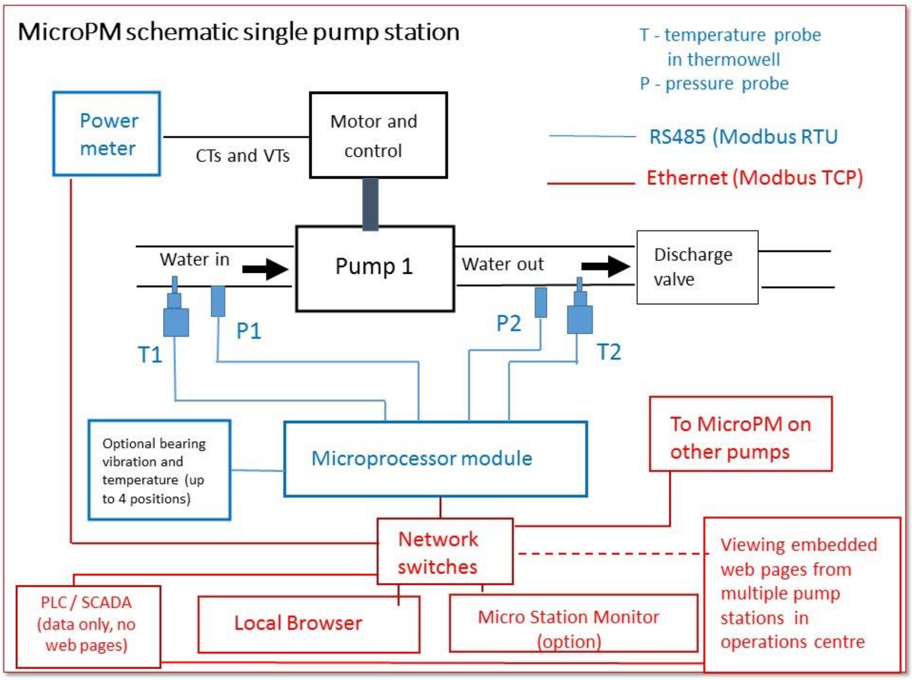
In contrast, the data obtained by the thermodynamic method in the previous Independent Electricity System Operator (IESO) (Canada) (Papa et al., 2013) programme was much more consistent.

2.3 CONTINUOUS EFFICIENCY MONOTORING

Field testing provides a snapshot/benchmark in time of efficiency while continuous efficiency monitoring is a permanent solution that covers all operational conditions providing real-time efficiency and therefore will rapidly red-flag pump problems. Continuous efficiency monitoring once installed minimises disruption to the pump station operation and limited resources.

Figure 4 shows a schematic of continuous thermodynamic MicroPM Pump Monitors from Robertson Technology which are in use at water authorities in the UK, USA, Canada, Singapore and Australia e.g. Water Corporation and Sunwater among others.

Figure 4: Schematic of continuous thermodynamic MicroPM Pump Monitors from Robertson Technology

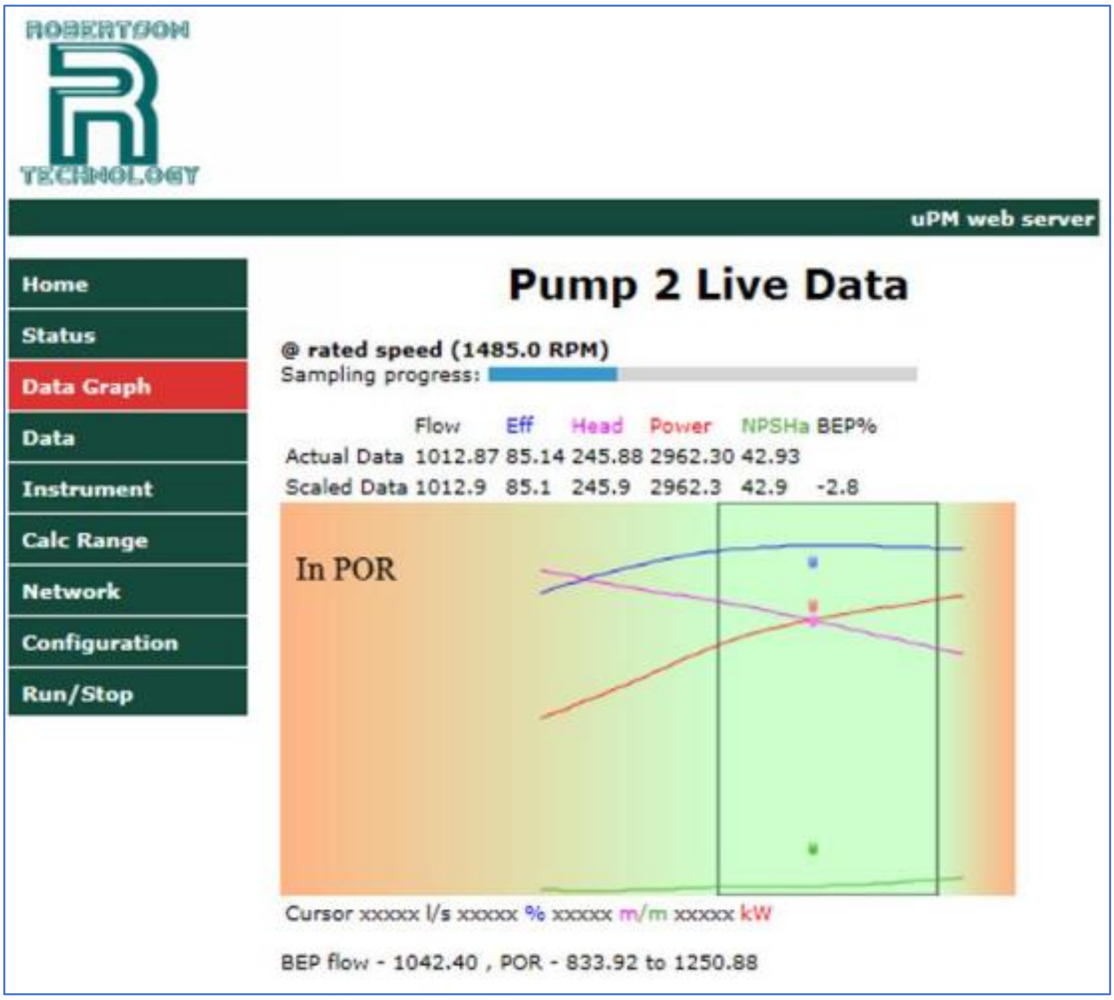


1

The MicroPM SCADA interface is via MODBUS TCP, MicroPM being a slave device. Information is held in specific registers that SCADA can read from and write to. SCADA then handles the retrieved data as required, presenting the information to operators in the most appropriate way and populating historian databases.

The MicroPM connects via wired Ethernet, though the subsequent network is not limited in any way, and can be either wired or wireless. MicroPM also provides an embedded webpage interface that is accessible to any suitably networked device that has a browser. This interface allows for status checking and live data monitoring, via a number of ways, including the comparison to pump curve data. It is also used for initial setup and configuration. Figure 5 shows the MicroPM Pump Monitor webpage dashboard.

Figure 5: MicroPM Pump Monitor webpage dashboard



Advanced features of the MicroPM Pump Monitors include station level pump scheduling functionality where it advises the user which pump combinations and VSD speed set points would provide their demand flow rate requirements in the most efficient and cost-effective manner.

Alternatively, continuous efficiency monitoring is done directly on SCADA systems or other dashboard e.g. Microsoft Power BI or on an open source web based product e.g. Prometheus using the conventional method where efficiency is calculated from the existing pump station telemetry data i.e. flowrate, pressure and motor power.

2.4 VIBRATION MONITORING

Vibration monitoring can detect efficiency deterioration, but it does not pick up on when efficiency starts to decline or quantify efficiency. Vibration monitoring is important and is complementary to efficiency monitoring. Increased vibration is an indicator once damage to the pump has occurred, mainly due to internal wear or from the pump operating outside its preferred operating range.

3 KEY PERFORMANCE INDICATORS

3.1 PREFERRED OPERATING RANGE (POR)

ISO 14414 'Pump system energy assessment' states that a pump's preferred operating range (POR) is defined by the limits at which the mean time between failures (MTBF) is cut in half. The POR limits are typically -20% and +10% of the flowrate at the pump's best efficiency point (BEP).

Operating inside these limits will help to ensure the pump reaches its design life. Operating outside of these limits rapidly increases the probability excessive wear and suction/discharge recirculation, while the pump is operating less efficiently than is possible.

Interventions to help operate a pump closer to its BEP include adjusting VSD speed, pump operating combinations, friction losses in pipework and pump impeller size.

A schematic of the POR is shown in Figure 6.

Figure 6: Preferred operating range (POR)

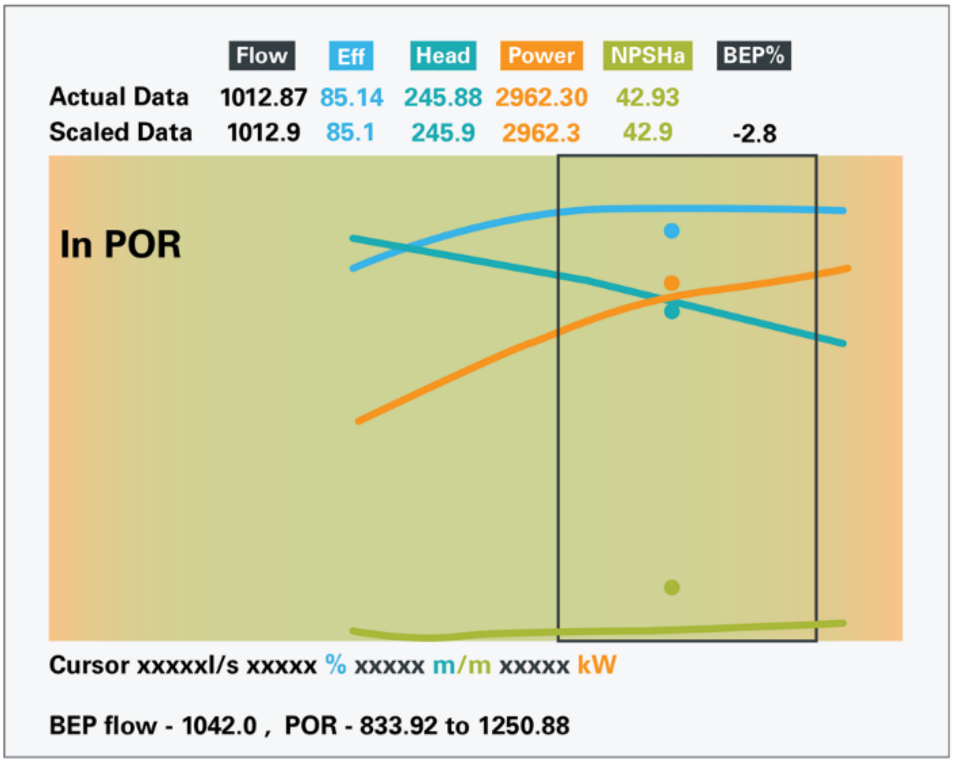
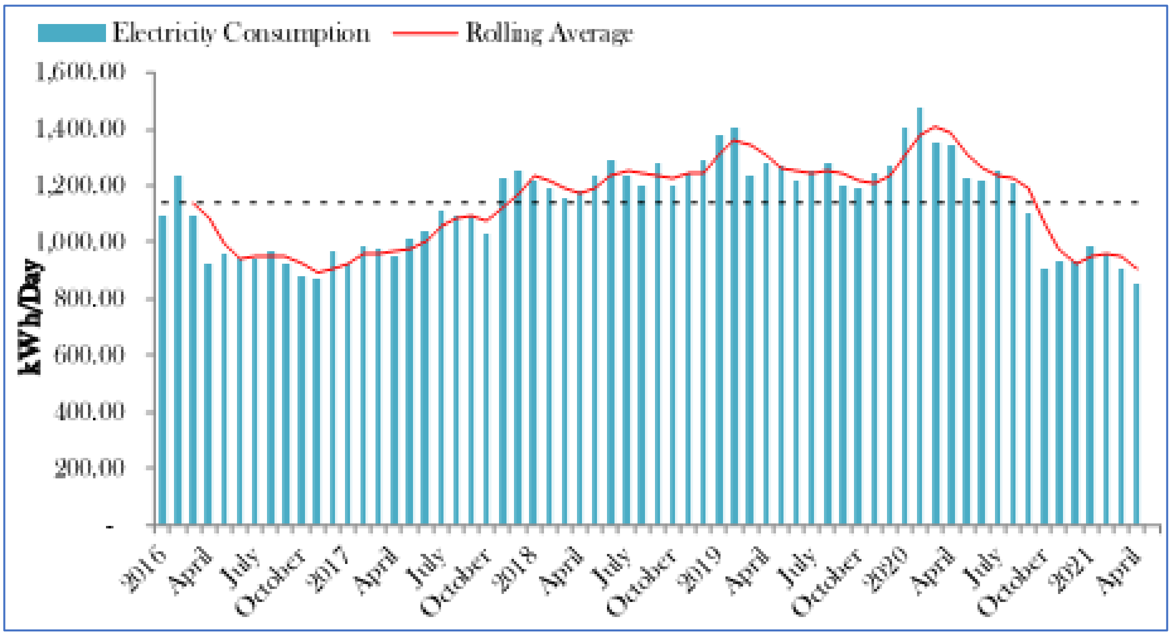


Figure 7 shows an example of how ensuring the pumps operate within their POR realises electricity cost savings.

Figure 7: Pharazyn pump station's electricity consumption



Pharazyn pump station had been increasing in electricity consumption for the previous four years, while the pumps were operating outside of their POR. Beginning in 2020 this trend sharply reversed and the electricity cost savings were due to replacing the existing 130 kW pumps with 160kW pumps which were operating at their BEP.

Figure 8 shows a photo of one of the new 160 kW pumps at Pharazyn pump station.

Figure 8: New 160 kW pumps at Pharazyn pump station

3.2 POTENTIAL ELECTRICITY COST SAVINGS

The potential electricity cost savings that can be achieved by scheduling pump overhaul to restore lost performance is calculated from the difference in the actual and the manufacturer's electricity consumption at the pump's normal operating duty.

$$\begin{aligned}&\textit{Potential electricity cost savings}\\&\qquad = (\textit{actual electricity consumption}\\&\qquad - \textit{manufacturer's electricity consumption})\ x\ \textit{electrcity cost}\end{aligned}$$

The units for potential electricity cost savings are $/year. The units for electricity cost is $/kWh.

$$\begin{aligned}&\textit{Actual electricity consumption}\\&\qquad = (\textit{volume pumped} \times \textit{total dynamic head} \times \textit{density} \times \textit{acceration of gravity}\\&\qquad \times \textit{run hours})\\&\qquad \div (\textit{calculated efficiency} \times \textit{drive efficiency} \times \textit{motor efficiency})\end{aligned}$$

Where run hours are the total hours for a year.

$$\begin{aligned}&\textit{Manufacturer's electricity consumption}\\&\qquad = (\textit{volume pumped} \times \textit{total dynamic head} \times \textit{acceration of gravity} \times \textit{density}\\&\qquad \times \textit{run hours})\\&\qquad \div (\textit{manufacturer's efficiency}\ x\ \textit{drive efficiency}\ x\ \textit{motor efficiency})\end{aligned}$$

3.3 OPTIMUM TIME FOR PUMP OVERHAUL

The optimum time for pump overhaul is accessed by plotting the accumulated potential electricity cost savings and refurbishment cost for consecutive years and selecting the year that has the lowest total cost.

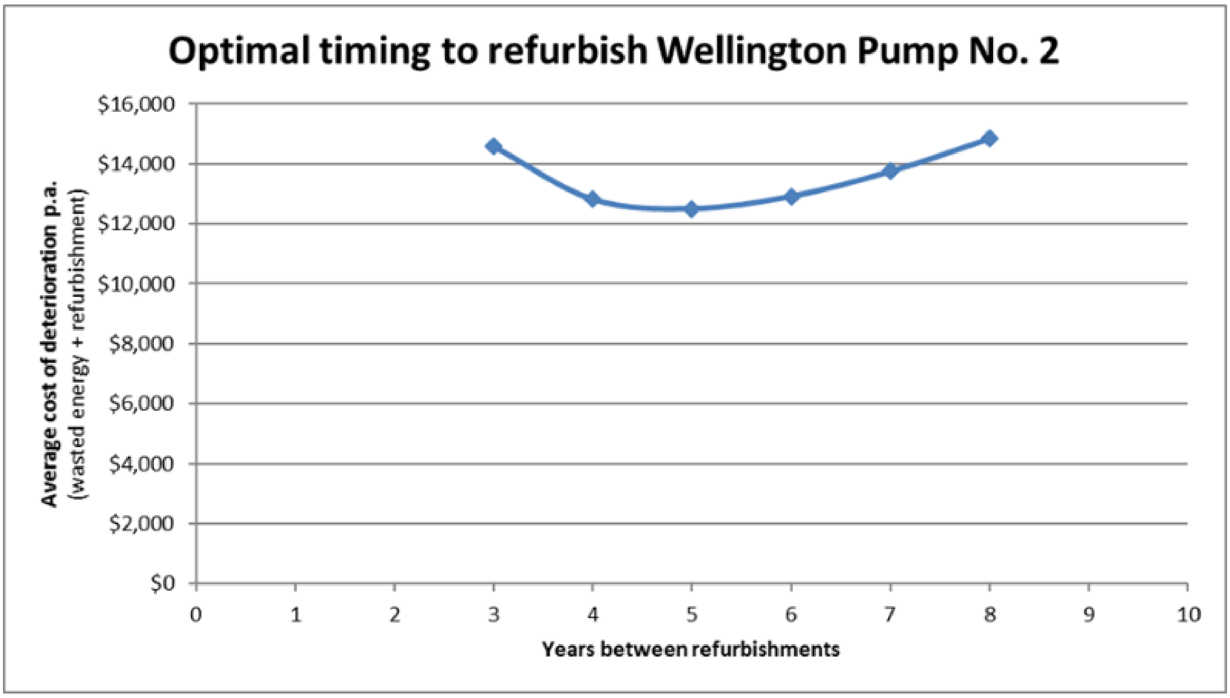
The cost of refurbishment will vary depending on the size and type of pump.

$$\begin{aligned}&\textit{Average cost of deterioration p.a.}\\&\qquad = (((\textit{potentail electricity cost savings}\\&\qquad \div \textit{efficiency drop})\ x\ \textit{no. years}\ x\ \textit{efficiency drop p.a.})\\&\qquad + \textit{cost of refurbishment}) \div \textit{no. years}\end{aligned}$$

Efficiency drop is the difference in the efficiency from two consecutive field tests. Efficiency drop p.a. is the efficiency drop divided by the no of years between the field tests. This assumes that no pump maintenance as occurred between field tests.

Figure 9 shows an example of optimum time for pump overhaul analysis, in this case the optimum overhaul time is every 5 years.

Figure 9: Optimum time for pump overhaul



3.4 BEST PUMP COMBINATIONS

Preferentially operating the most efficient, best matched pump(s) and speeds will meet the flow demands at the lowest energy and maintenance costs.

Efficiency may be used to determine the performance of single and multiple pump operating combinations in parallel. For a particular flow, the pump combination and set VSD speeds with the best combined efficiency should be preferentially selected.

Figure 10 and Table 1 show an example of best pump combination analysis. In this case the PPI_TDH efficiency KPI has been used such that a lower PPI_TDH value is more efficient than a higher one. As these pumps have VSDs the PPI_TDH values appear on the graphs as a range rather than a point.

Figure 10:   Best pump combination analysis

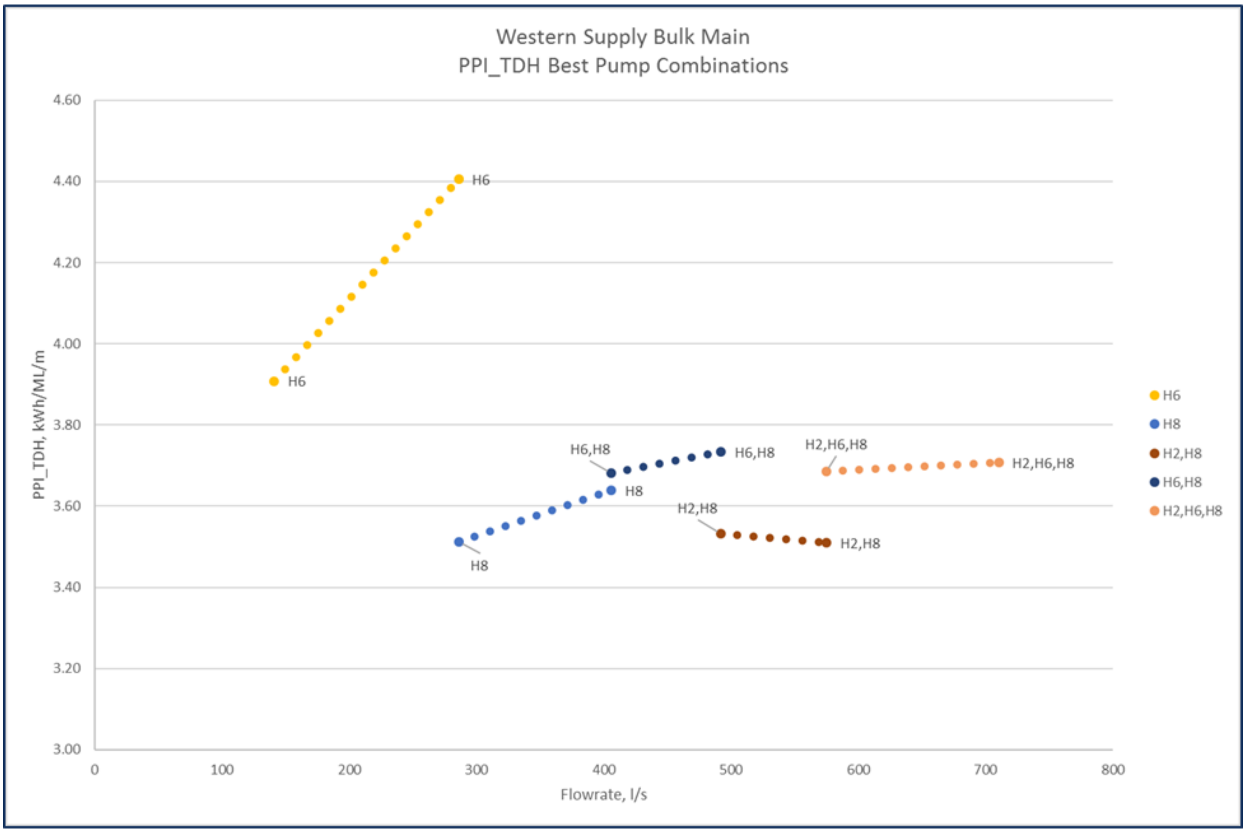


Table 1:   Best pump combination summary

Flow Range L/s	Best Pump Combination
Up to 400	H6 or H8
400 to 600	H6 & H8 or H2 & H8
Above 600	H2, H6 & H8

3.5 EFFICIENCY BENCHMARKING

Cardno has developed a pump efficiency benchmarking database for single pump operation using the PPI_TDH efficiency KPI calculated from highly accurate efficiency monitoring data to help water utilities identify the efficiency of their pumps.

PPI_TDH normalises the specific energy against the head produced by the pump, thus providing a more consistent comparison across pumps of different pressure ranges and independently from pump type or speed.

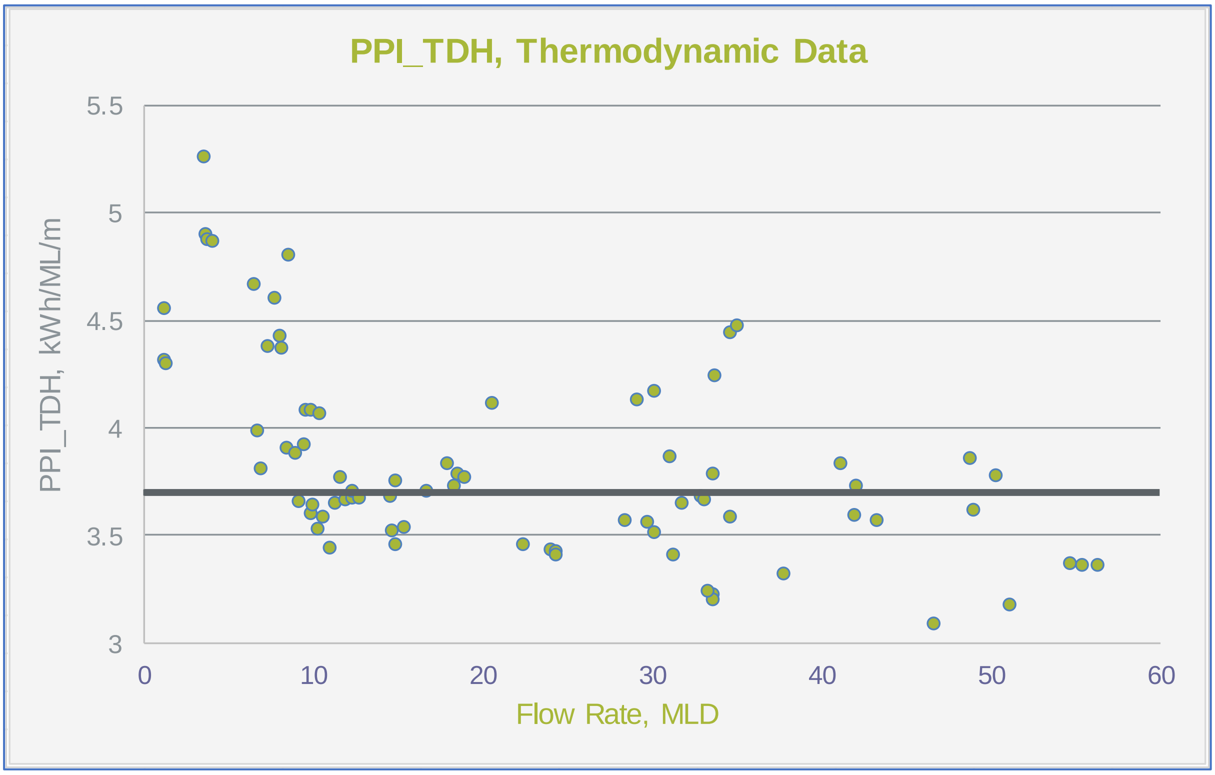
$$PPI_{TDH} = motor\ power\ consumption \div (volume\ pumped \times total\ dynamic\ head)$$

Where motor power consumption is in kilowatt-hours, volumed pump is in millions of litres and total dynamic head is in meters. The units of PPI_TDH are kWh/ML/m.

The best possible PPI_TDH value for a single pump operating is when its operating at its manufacturer's BEP.

Figure 11 shows the pump efficiency benchmarking database.

Figure 11: Pump efficiency benchmarking database



PPI_TDH efficiency values in the database vary from 3.1 to 5.3 kWh/ML/m and a value of less than 3.7 is defined for when a pump is operating efficiently, based on the 50th percentile of the database. If the PPI_TDH exceeds the 75th percentile, in this case a value of 4.1, potential electricity cost savings or operational efficiency improvements might exist for the particular pump and further analysis is recommended.

3.6 BENCHMARKING FOR NEW PUMPS

Efficiency testing on recently installed pumps will confirm that the pumps themselves are operating as they should and provide a benchmark for their capacity and efficiency. This also validates that the pump selection is within the actual operational parameters onsite.

3.7 MOST EFFEICIECNT PUMP REPLACEMENT

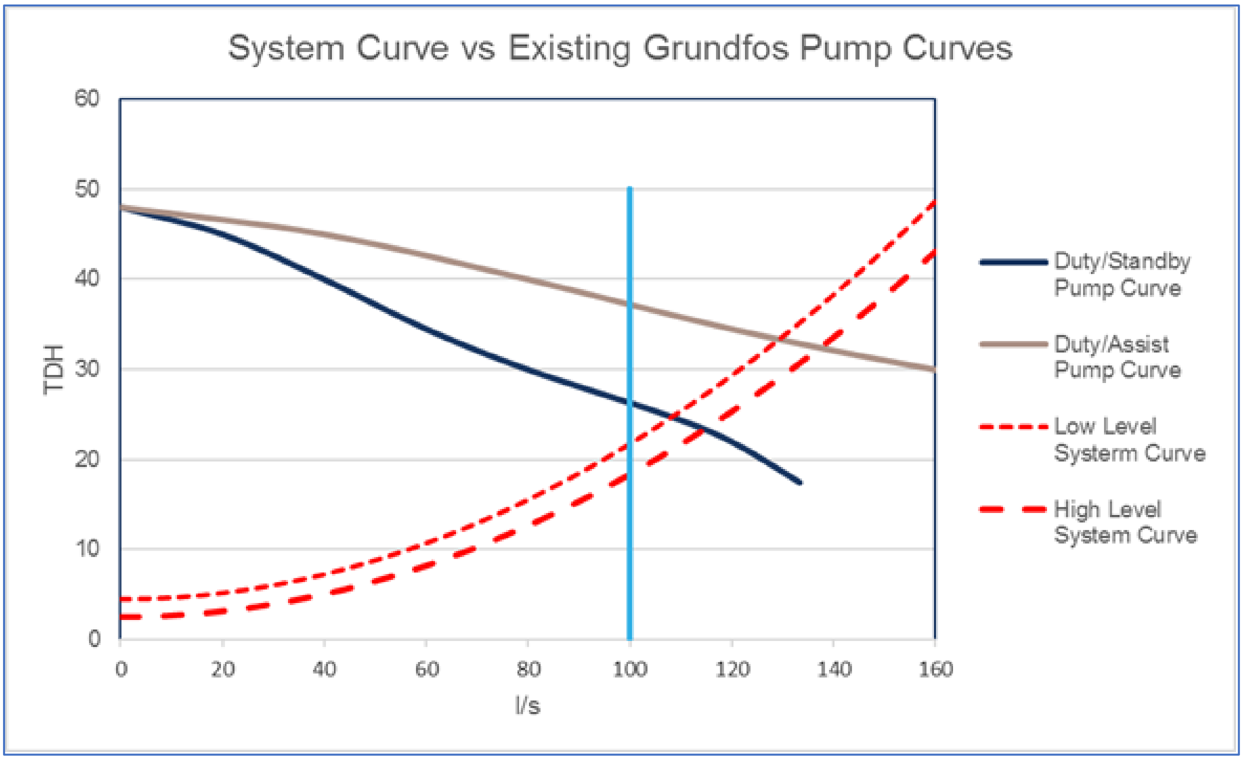
When considering pump replacement, the original pump selection may now not be the most efficient, as it may be oversized or undersized and therefore not operating at its BEP.

The flow demand and system conditions are often changing with population growth and upgrades being made to the network.

Measuring and/or calculating from as-built drawings the minimum and maximum system curves and matching potential new pump curves, based on the flow demand will ensure the most efficient pump is selected. Efficiency monitoring data from the existing pumps helps to validate the new pump selection.

Figure 13 shows new pump selection analysis.

Figure 13: New pump selection analysis



3.8 CALIBRATION OF NETWORK MODELS

Efficiency monitoring data provides accurate pumping system performance information used for validating upgrade design, network investigations, planning and modelling rather than relying on available data such as design reports which often do not reflect operational reality.

Network models can be calibrated with accurate flowrates from Thermodynamic efficiency monitoring, while providing validation for existing pump station flow meters.

3 CONCLUSIONS

Wellington Water have been implementing Thermodynamic pump efficiency monitoring using the Robertson Technology system for 11 years and found that the payback period was less than three months on their 34 bulk water pumps from the electricity cost savings alone.

To provide the fastest payback period it is recommended that pumps with highest energy use and/or criticality including their age and/or known performance issues should be prioritised for efficiency monitoring.

Precision class Thermodynamic measurement is covered by ISO 5198 and calculates efficiency from changes in enthalpy (energy per unit mass) of the liquid being pumped via suction and discharge temperature and pressure measurements. The Robertson Technology system has calibrated accuracy and repeatability to +/-0.5%. The system calculates the flowrate, without the need for a conventional flow meter, from the efficiency, pressure and motor power measurements.

The conventional method to calculate efficiency is from flowrate, pressure and motor power measurements. The flowrate is typically measured using an existing pump station flow meter or using volumetric measurements in the suction or discharge well or tank.

Many existing pump station flow meters are understood to have errors due to a number of factors including age, incorrect installation, fouling inside pipes and sensor drift over time. Thus, errors in the calculation of efficiency using the conventional method will possibly be too high for accurate calculation of the electricity cost savings and validating decisions for operational efficiency improvements.

Field testing provides a snapshot/benchmark in time of efficiency while continuous efficiency monitoring is a permanent solution that covers all operational conditions providing real-time efficiency and therefore will rapidly red-flag pump problems. Continuous efficiency monitoring once installed minimises disruption to the pump station operation and limited resources.

Vibration monitoring can detect efficiency deterioration, but it does not pick up on when efficiency starts to decline or quantify efficiency. Vibration monitoring is important and is complementary to efficiency monitoring.

The preferred operating range (POR) limits are typically -20% and +10% of the flowrate at the pump’s best efficiency point (BEP). Interventions to help operate a pump closer to its BEP include adjusting VSD speed, pump operating combinations, friction losses in pipework and pump impeller size.

The potential electricity cost savings that can be archived by scheduling pump overhaul to restore lost performance is calculated from the difference in the actual and the manufacturer’s electricity consumption at the pump’s normal operating duty.

The optimum time for pump overhaul is accessed by plotting the accumulated potential electricity cost savings and refurbishment cost for consecutive years and selecting the year that has the lowest total cost.

Preferentially operating the most efficient and best matched pump(s) and speeds will meet the flow demands at the lowest energy and maintenance costs.

Cardno has developed a pump efficiency benchmarking database for single pump operation using the PPI_TDH efficiency KPI calculated from highly accurate efficiency monitoring data to help water utilities identify the efficiency of their pumps. The PPI_TDH efficiency values in the database vary from 3.1 to 5.3 kWh/ML/m and a value of less than 3.7 is defined for when a pump is operating efficiently, based on the 50th percentile of the database. If the PPI_TDH exceeds the 75th percentile, in this case, a value of 4.1, potential electricity cost savings or operational improvements might exist for the particular pump and further analysis is recommended.

Efficiency testing on recently installed pumps will confirm that the pumps themselves are operating as they should and provide a benchmark for their capacity and efficiency. This also validates that the pump selection is within the actual operational parameters onsite.

Measuring and/or calculating from as-built drawings the minimum and maximum system curves and matching potential new pump curves, based on the flow demand will ensure the most efficient pump is selected. Efficiency monitoring data from the existing pumps helps to validate the new pump selection.

Efficiency monitoring data provides accurate pumping system performance information used for validating upgrade design, network investigations, planning and modelling rather than relying on available data such as design reports which often do not reflect operational reality.

Network models can be calibrated with accurate flowrates from Thermodynamic efficiency monitoring, while providing validation for existing pump station flow meters.

ACKNOWLEDGEMENTS

Malcolm Robertson, Robertson Technology

Geoff Williams, Wellington Water

Hywel Lewis, Wellington Water

Juan Martinez, Tauranga City Council

Noor Toumia, Hamilton City Council

REFERENCES

Grundfos, (2012) '*Meet the Energy Challenge Now'*

The Economist, (2021) '*What is the cheapest way to cut carbon?'*

Beebe, R. (2014) '*Predictive Maintenance of Pumps using Condition Monitoring'*

Badruzzaman, M., Cherchi, C., Sari, M.A., Pascua, E., Jacangelo, J.G., Bunn, S., Gordon, M. and Daly, C. (2017) '*Performance Benchmarking of Pumps and Pumping Systems for Drinking Water Utilities'* Water Research Foundation

Papa, F., Radulj, D., Karney B., Robertson, M. (2013) '*Pump Energy Efficiency Field Testing & Benchmarking in Canada*' Australia Asset Management for enhancing energy efficiency in water and wastewater systems, International Water Association, Marbella, Spain.

Livingston, D., Charakos, G., Farragher, C., Bartle-Smith, J., Robinson, K., Dancey, D. (2015) 'Australia-wide pump energy efficiency benchmarking demonstrates opportunities for improvement' OzWater, Australian Water Association, Sydney, NSW, Australia.