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Improving the energy efficiency of pumping systems

Maurice A. Yates and Ian Weybourne

ABSTRACT

Many pumping stations do not operate at anywhere near optimum energy efficiency. Work in the UK and overseas has consistently indicated that improving the operation and performance of pumping plant can make reductions in energy costs of between 30–50%. These savings may be generated by:

- refurbishing or replacing equipment that is worn or no longer appropriate for the duty;
- improving the scheduling of multi-pump systems to give the minimum operating costs for any particular demand;
- employing appropriate technology such as high efficiency motors and efficiency enhancing coatings;
- more effectively matching pump performance to demand by improving pump selection, impeller trimming or the use of variable speed drives;
- minimising hydraulic losses and installation effects;
- continuous monitoring of high energy use pumping plant.

Although several water companies are taking a proactive approach to the reduction of pumping costs there is still plenty of scope for improvement. This paper draws on the experience of carrying out many pumping cost reduction programmes in the UK and overseas. It examines the methodology behind these programmes, details potential energy saving areas and gives real examples of where significant savings have been made.

Key words | energy savings, life cycle costing, monitoring, pump efficiency, pump scheduling, pumping performance

Maurice A. Yates (corresponding author)
Ian Weybourne
Advanced Energy Monitoring Systems Ltd,
The Energy Centre,
Finnimore Industrial Estate,
Ottery St Mary,
Devon EX11 1NR,
UK
Telephone: +44 (0)1404 812204
Fax: +44 (0)1404 812603
Email: *info@yatesmeter.co.uk*
Website: *www.yatesmeter.co.uk*

THE COST OF PUMPING

Energy represents a massive investment for any water company and it is probably the second most controllable operating cost, after manpower. The annual electricity bill for a large water service company in the UK will be more than £20 million and account for about 10% of its total operating expenditure. Pumps use something like 70% of all the electricity consumed by the water industry at an annual cost of around £300 million.

Pumps

Typically the initial purchase price of a pump is between 1–5% of its life cycle cost, the balance being associated with energy consumption and maintenance.

There is a large difference between the maintenance of water pumps and the maintenance of sewage pumps.

However, in both cases, the energy cost is the most significant, being in water up to 95% of the life cycle costs and approximately 65% in the case of wastewater.

At 4 pence/kWh, a pump costs £1/kW/day to run; e.g. 100 kW = £35,000 per annum.

For operating costs to be minimised it is crucial that the relative importance of all the elements of the whole life cost profile are recognised and treated accordingly at the design and specification stage of projects. The pump specification determines not only the initial capital outlay but also the subsequent operating and maintenance costs (Figure 1). In the water industry where there is increasing

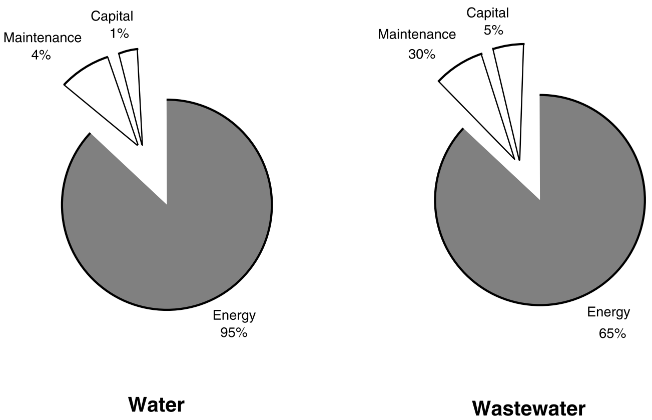

Figure 1 | The whole life cost of a typical water and wastewater industry pump-set.

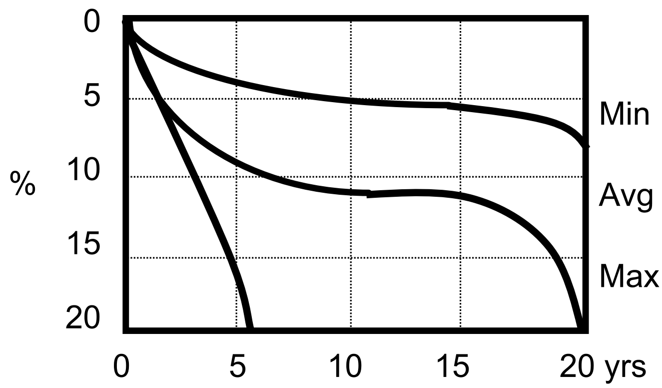

Figure 2 | Pump efficiency deterioration with age.

Table 1 | Monitoring frequency

Size (kW)	Duty/standby	Multipump operation
50	3 year	3 year
100	2 year	2 year
150 +	1 year	Continuous

pressure to reduce capital expenditure and, in some cases, a fairly extensive and complex supply chain too much emphasis is often allocated to the initial purchase price which can lead to higher operation and maintenance costs.

Even if the most appropriate and efficient pump has been selected for the duty then there will inevitably be some increase in running costs with age as:

- wear ring clearances open up due to wear and erosion, increasing internal leakage losses;
- impeller and casing surfaces become roughened, due to corrosion and cavitation damage, increasing hydraulic friction;
- the shape of impeller and casing flow passages are changed due to corrosion and erosion.

The magnitude of this deterioration and the rate at which it occurs depends on the pump design, the duty, and the installation (Figure 2). Experience from the UK and around the world suggests that on average the efficiency of a typical pump in-service will have deteriorated up to 15%. The time taken for this wear will be very dependent upon the fluid being pumped, the NPSHa available and the operating point of the pump with respect to its best efficiency point (BEP). Our experience is that this shortfall may occur in as little as 1,000 h or as long as 100,000 h. It is for this reason that we recommend that a pump be tested on commissioning and a regular pattern of testing be incorporated into the operating procedures.

This pattern will vary, dependent upon the circumstances outlined above, but a typical water installation may be on commissioning one year later (for warranty consideration) then in accordance with the above table.

The problem is that in most cases this deterioration will go undetected. The pump will still perform but the operating costs will have significantly increased.

Pumping systems

Pumps should not be considered in isolation. They are in integral part of the systems in which they operate. The system characteristic defines the operating point of the pump and the energy required to produce the desired flow rate. As with pumps there is often a need to strike a balance between capital expenditure and operating costs. For example, increasing pipework diameters reduces system hydraulic losses and, hence, operating costs but increases capital costs (Figure 3).

In terms of pumping the water industry is characterised by significant over-capacity, a variable demand and, in some cases, variable electricity tariff rates. This means

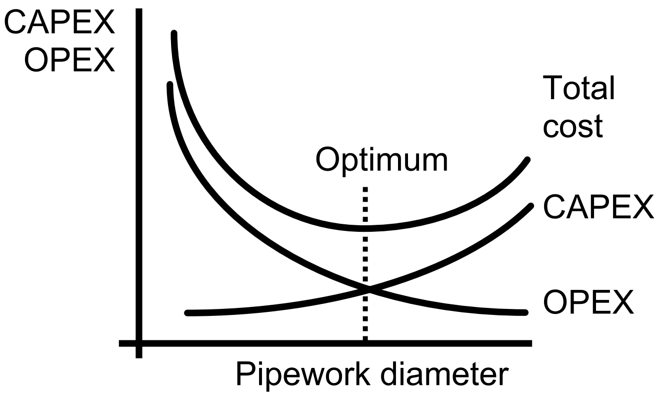

Figure 3 | Optimising plant costs.

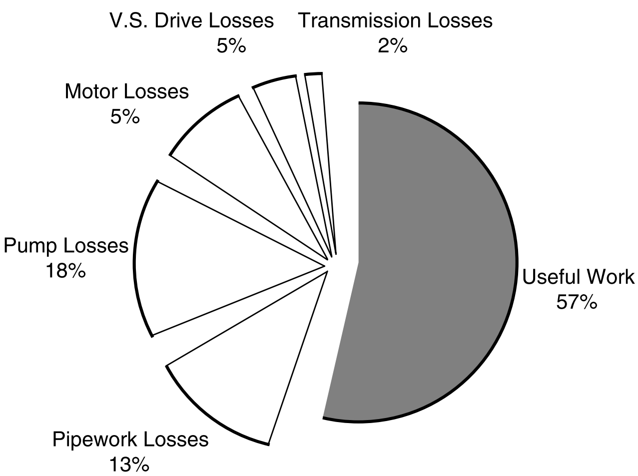

Figure 4 | Energy balance for a typical water pump-set.

that there is a great deal of operator discretion involved in the selection of pump schedules to meet a particular demand profile. Often these decisions are based on minimal, or out of date information on the efficiency and hydraulic performance of the pumping plant and the systems that they operate in. Clearly, some of these operating schedules will be significantly more expensive than others.

The original design and operating procedure for a particular pumping station, or combination of stations, may have been well thought out when the system was first conceived but this could have been 10, 15 or even 20 years previously. Systems age and are often modified. Functional requirements also change. As a result the efficiency, effectiveness and reliability of pumping systems can be

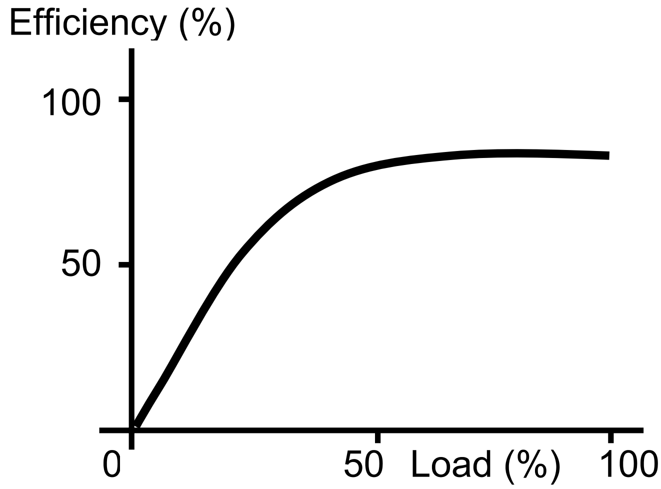

Figure 5 | Typical efficiency load profiles for motors and inverters.

severely compromised. When the efficiency of the complete pumping system is considered then work in the UK, and from around the world, suggests that improving the operation of pumping plant can lead to overall reductions in energy costs of between 30–50%.

From wire to water

The function of most pumping systems in the water industry is to transfer water or wastewater from one location to another at minimum cost. The input to this process is electrical energy which is converted into mechanical energy by the motor and ultimately hydraulic energy by the pump (Figure 4). This is not a 100% efficient process and energy is inevitably lost along the way. The source of these inefficiencies may include:

- transformer losses;
- cable losses;
- variable speed drive losses;
- motor losses;
- pump losses;
- pipework losses.

Of these the transformer and cable losses are generally small, of the order of 2–4% for a well-designed system. However, if cable sizes are underestimated or based on the minimum safe size to prevent overheating then these losses can become significant.

The efficiency of modern variable speed drives is around the 95% mark and motors come in at about 90–96%. In addition, the efficiency of variable speed drives and motors remains fairly constant across the load range, down to something like 50% of their design load (Figure 5). Unfortunately, the same is not true of centrifugal pumps. The as-new, peak efficiency of the type of centrifugal pumps used in the water industry can vary between 60–90%, and the efficiency characteristics of these pumps are strongly flow (load) dependent (Figure 6).

The hydraulic energy produced by the pump is used to lift the water or wastewater from the source to the point of delivery and provide the additional energy required to overcome the hydraulic friction losses in the pipework and fittings (Figure 7).

The relative importance of these losses is best illustrated by an example. If we take a fairly common water pumping application and assume we want to deliver 102 l/s against a total head rise of 100 m then using the data given below we can calculate the losses.

Flow rate (Q)	0.102 m^3/s
Static head (H_s)	80 m
Head loss due to friction (H_f)	20 m
Density of water (ϱ)	1000 kg/m^3
Pump efficiency (η_p)	80%
Motor efficiency (η_m)	95%
Variable speed drive efficiency (η_d)	95%
Transformer and transmission efficiency (η_t)	98%

Useful work done

$$= \rho.g.Q.H_s = \frac{1000 \times 9.81 \times 0.102 \times 80}{1000}$$

$$= 80\,\text{kW}$$

Pipework losses

$$= \rho.g.Q.H_f = \frac{1000 \times 9.81 \times 0.102 \times 20}{1000}$$

$$= 20\,\text{kW}$$

Power to pump

$$= \frac{(80+20)}{\eta_p} = \frac{100}{0.8} = 125\,\text{kW}$$

Pump losses

25 kW

Power to motor

$$= \frac{125}{\eta_m} = \frac{125}{0.95} = 131.5\,\text{kW}$$

Motor losses

6.5 kW

Power to drive

$$= \frac{131.5}{\eta_d} = \frac{131.5}{0.95} = 138\,\text{kW}$$

Drive losses

6.5 kW

Input power

$$= \frac{138}{0.98} = 141\,\text{kW}$$

Transmission losses

3 kW

Overall Pumping Efficiency (η_{ov})

$$= \frac{80 \times 100\%}{141} = 57\%.$$

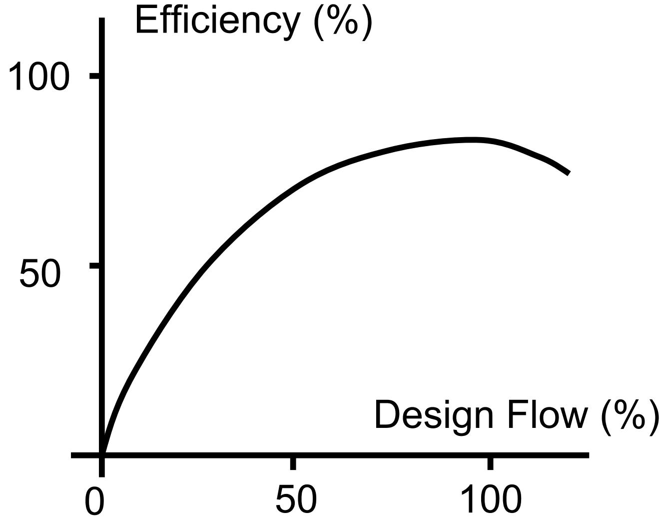

Figure 6 | Efficiency load profile for a centrifugal pump.

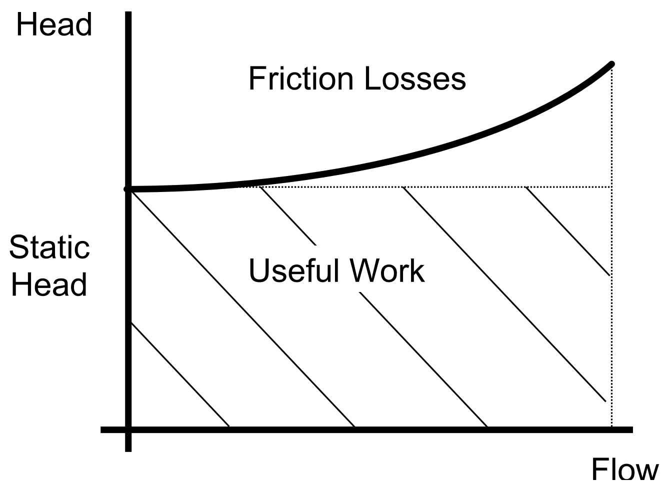

Figure 7 | System characteristics.

This relatively simple analysis demonstrates how important the pump and pipework losses are to the overall efficiency of the pumping system. In this example these losses account for 43% of the total input power (Figure 4).

We could have arrived at this same result for the overall efficiency by defining a system efficiency (η_s) as:

$$\eta_s = \frac{H_s}{H_s + H_f} = \frac{80}{80+20} = 0.8$$

Then:

$$\eta_{ov} = \eta_p . \eta_m . \eta_d . \eta_t . \eta_s = 0.57$$

This is important as we can now express the input power (P_{gr}) directly as:

$$P_{gr} = \frac{\rho . g . Q . H_s}{\eta_{ov}} = 141\ \mathrm{kW}$$

It also allows us to define another useful parameter for the comparison of pumping system performance known as specific power consumption (P_s):

$$P_s = \frac{P}{Q} = \frac{\rho . g . H_s}{\eta_{ov}} = \frac{W_s}{m^3}$$

Specific power consumption is often expressed in more familiar units such as kWh/Ml.

$$P_s = \frac{141 \times 1000}{0.102 \times 3600} = 384\ \frac{\mathrm{kWh}}{\mathrm{M1}}$$

This is a useful indicator for comparing the same system before and after some improvements have been made (e.g. pump refurbishment). However, if we want to compare the performance of different systems we need to take this one step further and consider the energy consumed per metre of static head. In which case for this application:

$$P_s = \frac{P_{gr}}{Q . H_s} = \frac{141 \times 1000}{0.102 \times 80 \times 3600} = 4.8\ \frac{\mathrm{kWh}}{\mathrm{M1.m}}$$

If the power consumption and total flow are metered on-site we can identify expensive systems where there is significant potential to make savings through reductions in power consumption. We should concentrate our efforts on sites that have a high electricity bill and a relatively high specific power consumption (Figure 8).

COST REDUCTION PROGRAMMES

Energy saving initiatives are not something new. In the late 1980s and early 1990s several water companies carried out major pump improvement programmes to deliver significant reductions in energy consumption. More recently the focus has been on negotiating very competitive contracts with the privatised electricity supply companies. The savings made in this area have outweighed the potential benefits of any programme aimed at the reduction of consumption.

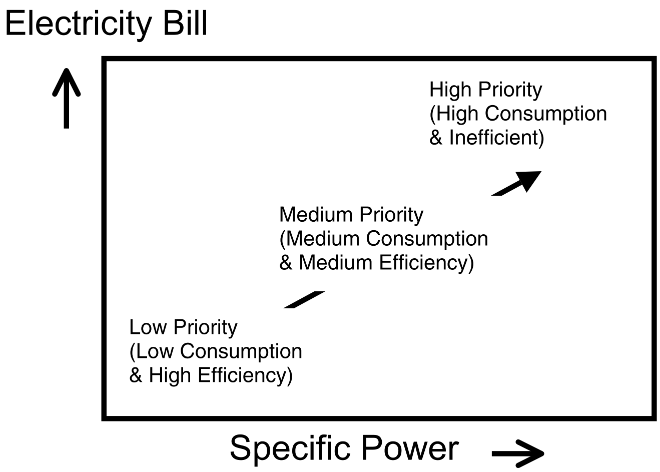

Figure 8 | Identifying cost saving opportunities.

However, times have changed and the prospects of similar reductions in tariff rates are very limited. The threat of the impending 'Climate Change Levy' and pressure from the regulator means that companies are again looking hard at energy consumption and best operating practices. It is not just simply a question of making savings. If companies do not address energy efficiency then their costs will inevitably rise.

The mechanism

The first step in the process has to be to develop an energy policy for the company, which includes some meaningful numerical targets and has recognition and support at Board level. This will lead to the definition of the financial criteria for the acceptance of energy saving projects. As appropriate, these could be based on the simple payback period, which is often satisfactory for most applications, net present value (NPV) or the internal rate of return (IRR). It is useful if a fairly simple and brief form can be developed to gather information on the technical objectives, the scope and cost of the work to be carried out and the estimated savings. This enables project information to be collected and evaluated cost effectively and consistently.

The next step is to identify the systems that should be considered in detail. This is usually done on the basis of energy usage. It is often the case that 80% of the energy costs will be associated with 20% of the plant. This makes the assumption that the greatest potential savings are associated with high-energy use plant, which may not be the case, but it is a useful starting point. Theoretically, more attention is given to assessing the whole life cost of high value, critical plant at the design stage. Depending on the quantity and quality of energy and flow metering which has been carried out it may be possible to refine the study to include more discretionary parameters such as specific power consumption.

Having produced a 'hit-list' of high cost plant an assessment has to be made of the potential savings and the investment required in each case. It is important at this stage to obtain information on the current and future operational requirements. It would be embarrassing to develop an elegant energy saving scheme only to find that the plant is to be 'moth-balled' before it can be completed. Testing and monitoring will inevitably be required to reliably quantify the potential savings. This can become quite complex particularly when there is a large fluctuation in demand, significant over capacity and a high degree of interaction between individual assets.

To help address some of these issues it may be appropriate to continuously monitor the efficiency and performance of some energy intensive pumping systems. The technology is now available, particularly with the development of the Internet, to take this data and analyse it remotely. The advantage of this approach is that it reduces the burden on operations and it puts the data into the hands of the personnel best suited to make cost effective use of it.

It is only at this stage that all the information required to carry out a financial evaluation of individual projects has been generated. This is an important point because it shows that to manage the energy bill and identify and promote an adequate flow through of energy saving projects there is a need to provide engineering resources to support the core activity.

It is interesting to explore what it is worth investing to generate reductions in energy consumption. We have looked at a range of companies and in general an investment of 5–10% of the electricity bill over five years, the regulatory cycle, can generate very respectable internal rates of return of around 30%. This assumes a target energy saving of 10–20% three years after making the initial investment, which should be readily achievable. The investment profile is typically front end loaded and is a mix of staff/consultancy costs (30%) and engineering works (70%).

Finally, there is a need to carry out the work and demonstrate that the savings have been achieved and are being maintained. To ensure that maximum benefit is obtained from any investment it is important to publicise the results of individual projects throughout the company.

Traditional barriers to progress

Experience has shown that in many cases energy cost reduction projects have not progressed despite a sound technical case being developed. There are many reasons for this but most of them are related to the required finance package. Unfortunately, engineers and accountants are still not able to speak the same language. The most common reasons for not progressing with a particular project are as follows.

Risk

There are two elements of risk to be considered. There is the risk that the costs of any preliminary work required to identify a portfolio of savings related projects may not be recovered. Then, there is the risk that individual projects may not be successful and deliver the anticipated savings.

Budget constraints

If capital investment is required to deliver the savings then it could be that there is no budget for activities of this type, which arise part way through the planning process. Even if there is a budget available it may be difficult to release funds at relatively short notice. In some cases, the investment required and the savings accrued can be allocated to different budgets, leading to internal conflicts.

One way to overcome these barriers is to enter into a ‘risk–reward’ relationship. As the payback periods for projects of this type are often of the order of two to three years with very attractive rates of returns they can attract third party finance. The third party, which could perhaps be an electricity supplier, financial institution or equipment supplier, makes the initial investment required in return for a proportion of the savings generated. Essentially, the water company is offering to share the rewards in return for the third party carrying some of the risk.

For this approach to work it is important to have a clear understanding at the outset of how the base line costs are to be defined and the savings measured. There is also a need to have an independent source of expertise to:

- provide a reliable audit trail;
- confirm current costs, quantify the potential for savings and specify the work required;
- project manage the work and subsequently carry out any tests required to confirm the magnitude of the savings.

The advantage of effectively outsourcing this function is that the contract placed with the service provider can be performance related. This drives the initiative forward. Traditional in-house energy management programmes tend to be under resourced and seen as a part-time activity. Therefore, the major benefits to water companies of this approach are that it overcomes the traditional barriers to energy management, specifically it:

- is self-financing, with any expenditure required being funded from the savings generated;
- delivers significant, on-going savings in operating expenditure;
- provides a mechanism for improving the performance and reliability of plant and equipment without the need for significant up-front capital expenditure;
- is a low risk option.

EXAMPLES OF ENERGY SAVINGS

The data presented here have been produced from real, on-site tests using the Yatesmeter for measuring pump efficiency and performance. The main attractions of this instrument are that:

- it enables pump efficiency and performance to be accurately determined on-site;
- the equipment is easily installed;
- test work can be carried out with the minimum disruption to normal operations;
- it does not rely on existing, installed flow metering equipment.

Pump efficiency is determined from measurements of the differential head and temperature rise across the pump and using information on the thermodynamic properties of the liquid being handled. If the power absorbed by the motor is also measured the flow rate can be determined and a full set of pump performance curves produced.

Pumping station A

At this water pumping station six high lift pumps draw filtered water from a common suction main and deliver it through a common discharge main to feed a distribution network and a service reservoir. The station houses six horizontal, split-case pumps. Two of the pumps are rated at 158 l/s and four at 316 l/s. Under normal conditions one 158 l/s pump and two 316 l/s pumps run continuously in parallel to produce the nominal station output of 790 l/s against a head rise of 62 m. This example relates to the refurbishment of one of the 158 l/s pumps.

The pump was tested on-site before and after pump refurbishment and a full set of performance curves were produced for comparison with the manufacturers original test data (Figure 9). The pump refurbishment involved:

- removing the pump from site;
- grit blasting of all surfaces to remove corrosion products;
- renewal of pump wear rings to reduce leakage losses;
- coating of the pump casing and impeller shrouds with a polymer resin coating designed to improve the surface finish, and hence reduce friction losses, and resist further corrosion.

The pump performance at the operating point (i.e. with three pumps running) before and after refurbishment is compared in table 2.

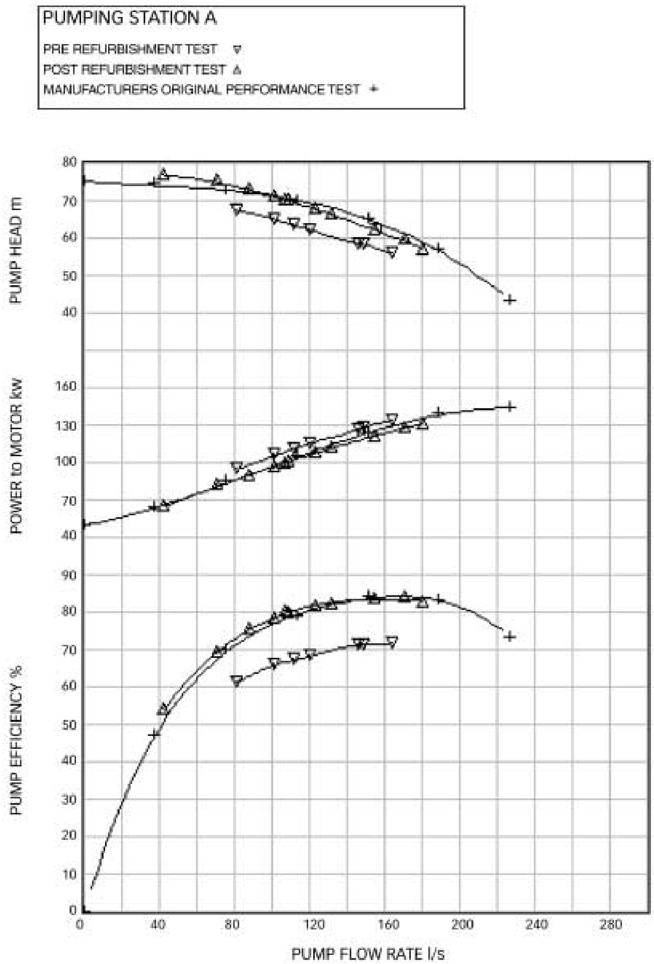

Figure 9 | Pump performance curves—pumping station A.

As this pump normally runs for 12 hours a day, 365 days a year, the estimated annual savings, assuming the same total pumped volume before and after refurbishment and an electricity tariff of 4 pence/kWh is:

$$= (264 - 218) \times \frac{122 \times 3600 \times 12 \times 365}{10^6} \times 0.04 = £3,540$$

In this case the refurbishment costs were higher than expected for this type and size of pump owing to the extensive amount of work required. However, the payback period was still 2.2 years even based on a fairly modest 50% utilisation.

Table 2 | Pump performance improvement

Paramater	Before refurbishment	After refurbishment	Change (%)
Flow rate (l/s)	122	154	+ 26
Motor input power (kW)	116	121	+ 4.3
Pump efficiency (%)	69	83	+ 20
Specific power (kWh/Ml)	264	218	– 17

Pumping station B

This station supplies treated water to two service reservoirs through a common discharge main. There is also an intermediate take-off to feed a small town. The station contains seven multi-stage, horizontal, radially split casing pumps. Each pump is designed to deliver 345 l/s against a head rise of 160 m. Typically, under normal conditions two pumps are operated in parallel for 16 h and three pumps in parallel for the remaining 8 h. The pump duty is shared so that each pump runs for approximately the same period of time.

Several potential energy saving options are currently being considered for this station, which vary in capital cost, complexity and the magnitude of the estimated savings. These include improving the scheduling of the existing pumps, trimming pump impellers, incorporating variable speed drives and providing new pumping plant.

Pump scheduling

The system characteristics are such that at the average maximum flow condition (1,113 l/s) the total head required is 150 m. At the average minimum flow condition (742 l/s) this falls to 133 m, which is significantly less than that anticipated when the station was originally designed. Therefore, to prevent the pump flows increasing beyond the design point and overloading the pump motors their discharge valves are throttled to maintain the system head at about 155 m. The on-site performance of all seven pumps at this condition is given in table 3.

Using these figures and assuming that all the pumps operate for the same time the total volume pumped each year is 27,279 Ml and the power consumed is 16,180 MWh. At a tariff rate of 4 pence/kWh this corresponds to an annual electricity bill of £647,189. However, we can see from the table that pumps 2, 6 and 5 have the lowest operating costs. If we were to run these pumps exclusively then we could pump the same total volume of water and save £8,163 a year. Although the cost of implementing this improved schedule is negligible the estimated savings are only of the order of 1.3% of the current electricity bill.

Impeller trimming

Throttling the pump discharge valves to maintain the head at 150 m, particularly at the low flow condition when only two pumps are operating, is clearly inefficient. Although throttling the pumps back in this way prevents

Table 3 | Pump station 'B' individual pump performance table

Pump	1	2	3	4	5	6	7
Flow rate (l/s)	360	390	371	364	379	371	360
Motor input power (kW)	784	820	792	775	805	783	782
Pump efficiency (%)	75	77	76	76	77	77	75
Specific power (KWh/Ml)	605	584	593	591	590	586	603

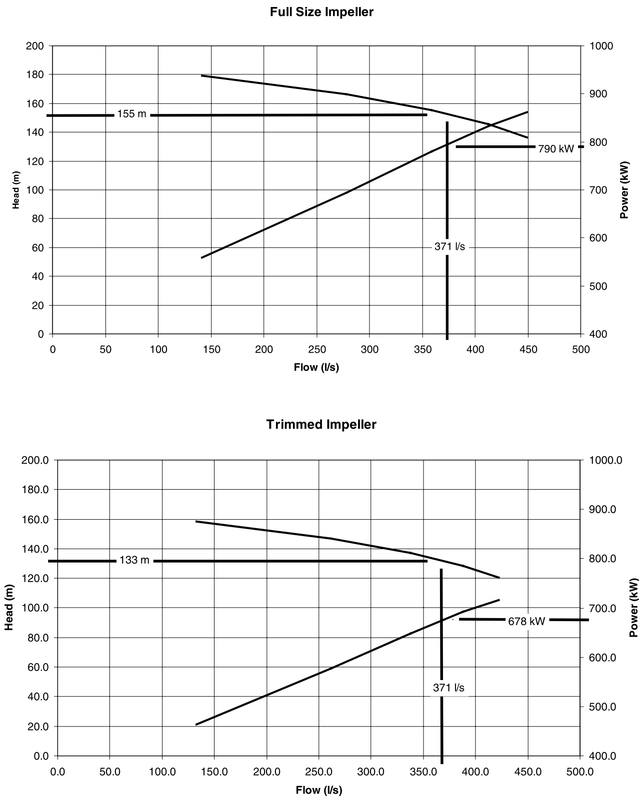

Figure 10 | Full size and trimmed impeller characteristics—pumping station B.

overloading the motors energy is wasted in overcoming the additional 17 m head loss.

One way to overcome this would be to reduce the outside diameter of the impellers. This would enable the pump characteristic to be more effectively matched to the system requirements. The pump affinity laws tell us that for a centrifugal pump: flow α diameter, head α diameter^2, power α diameter^3.

Using these laws we can estimate what reduction in impeller diameter would be required to make the combined pump characteristic, with two pumps running in parallel, intersect the system characteristic at a flow of 742 l/s and 133 m head (Figure 10). The calculations show that if the outside diameter of the impellers is reduced by about 5% then two pumps running in parallel would meet this condition. This would remove the requirement to throttle the pumps and reduce the individual motor input power to 678 kW. Three trimmed pumps running in parallel would deliver a total flow of 970 l/s against a head rise of 145 m. At this condition the individual motor input power is 635 kW.

Using these figures and assuming the same total volume pumped each year the power consumed is reduced by 1,704 MWh. At a tariff rate of 4 pence/kWh this corresponds to an annual saving of £68,167. This is equivalent to a saving of just over 10% of the annual electricity bill. Even allowing for three pumps to be removed from site, refurbished, impellers trimmed and returned to service the estimated payback is less than 2 years.

The same effect could be achieved using variable speed drives, which would allow a greater degree of control, but the savings would not be as high as the efficiency of the drives would also have to be taken into account.

Replacement pumps

The equipment currently installed is nearly 20 years old and using more modern and efficient pumps and motors would significantly reduce the operating costs.

The system requirements vary from 742 l/s at 133 m head up to 1113 l/s at 150 m head. The high head requires the use of multi-stage pumps and to maintain a reasonable pump specific speed, and hence efficiency, three pumps are required to cover the range of duties. This application is not particularly well suited to variable speed drives because the system characteristic is relatively flat due to the high static head contribution.

If the pumps were to be replaced the same generic type of pump would be used but they would be rated at 371 l/s and 133 m head. The efficiency of a modern pump of this size and type would be expected to be in the region of 80–84%. The pumps would be fitted with high efficiency motors giving an efficiency of 96%.

Taking these values for the pump and motor efficiencies and the same total volume pumped each year, the power consumed is reduced by 2,598 MWh. At a tariff rate of 4 pence/kWh this corresponds to an annual saving of £103,938. This is equivalent to a saving of 16% of the annual electricity bill. The savings are so significant because they include the effect of opening the throttled discharge valves and using more efficient plant and equipment.

CONCLUSIONS

The cost of the electricity used by pumps in the water industry is important. These costs can be controlled and significantly reduced through the application of appropriate technology and resources.

Pump and pipework losses have the most significant impact on the overall efficiency of a well-designed pumping system. However, pumps should not be considered in isolation. The performance of individual components is important but the way that the system is operated and its overall efficiency needs to be addressed.

Systems degrade, are modified and generally evolve and, therefore, there is a need to continually review their efficiency and performance. To be effective pump improvement programmes need to be focussed on the areas where significant savings can be made.

Generally, payback periods on pump efficiency improvement projects are of the order of two to three years, generating attractive rates of return. Depending on suitability, projects can attract third party finance and support 'risk–reward' contracts.

Energy is a Board-level issue. It is important to develop a company energy policy to provide the recognition, support and impetus required to deliver real and ongoing savings.

ABBREVIATIONS AND NOTATIONS

H_s	Static head (m)
H_f	Friction head (m)
P_{gr}	Input power
P_s	Specific power consumption
Q	Flow (m^3/s)
η_d	VS drive efficiency
η_m	Motor efficiency
η_{ov}	Overall efficiency
η_p	Pump efficiency
η_s	System efficiency
η_T	Electrical transmission efficiency