ENERGY EFFICIENCY ASSESSMENT OF PUMPING STATIONS: DIAGNOSIS AND IMPROVEMENT MEASURES ANALYSIS

Bernardo Manuel Veiga Alçada Mendonça Batista
Instituto Superior Técnico, Lisboa, Portugal, 2020
bernardo.batista@tecnico.ulisboa.pt

ABSTRACT

The aim of the current research is the development and application of a methodology for the energy efficiency assessment of pumping stations (PS) in water supply and waste water systems. This methodology is based on the analysis of available data associated to the pumping stations characteristics (e.g., number of pumps, rated discharge/head, installed power) and operating conditions (e.g., discharge, head, energy consumption time series). Three categories of key-performance indicators (KPI) related to the energy efficiency, technical performance and operating cost of the pumping stations are proposed to carry out the diagnosis. Different improvement measures (infrastructural, operation, maintenance, others) are established for improving energy efficiency. The proposed methodology is composed of five main steps: 1. Key-performance indicators establishment; 2. Data collection and KPI calculation; 3. Diagnosis and priority identification; 4. Improvement measures analysis; 5. Economic analysis. The methodology is applied to the PS of three case studies, each associated with a different utility, corresponding to a sample of 221 PS, considered representative of the water and waste water PS in Portugal. This allowed the identification of specific problems in each PS and also the identification of improvement measures, namely, operation of electric pumps at the maximum efficiency point, installation variable speed drives, improving the monitoring and data recording system, rehabilitation or replacement pumps or their components and pump maintenance. Additionally, a detailed analysis is carried out to the five least efficient PS of each utility, with higher potential for reducing energy consumption. Water supply pumping stations have typically higher installed power, higher energy consumption and more reliable and accurate available data, unlike wastewater pumping stations which have low installed power, low energy consumption and, often, unreliable monitoring data.

Keywords: Pumping station, energy efficiency, utility, water supply, waste water, performance indicators.

1 INTRODUCTION

Pumping stations are essential assets of public water supply and waste water systems, according to the Portuguese water regulator (*Entidade Reguladora dos Serviços de Águas e Resíduos*, ERSAR). Their function is to provide energy to the fluid, in order to allow it to be conveyed over topographical variations and to maintain pressure and flowrate levels appropriate to the demands. In water supply and waste water systems, it is essential to ensure adequate pumping efficiency levels to reduce energy consumption and associated costs, as well as to ensure that the equipment performs well during its service life. It is therefore essential to develop methodologies for diagnoses and assessment the pumping stations performance. This study develops and applies methodology for the energy efficiency assessment of pumping stations in water supply and waste water systems, based on a set of key performance indicators that allowed the analysis of the PS efficiency and the identification of intervention priorities. The methodology also provides guidance for the interventions designed to improve performance, to reduce costs and to ensure system sustainability.

2 LITERATURE REVIEW

Any pumping station necessarily includes two parts: the pumping unit, consisting of the pump-motor; and the hydraulic components consisting of pipes, fittings and valves (Stoffel, 2015). Experience shows that failures in pumping systems often result from the inadequate operation, deficient design of the system or poor installation conditions of the pump and associated components. It is, therefore, essential that all the pumping station components, including "non-pump" elements, receive the required attention (Heinz and Budris, 2015). In the diagnosis of the operation of pumping systems some of the factors that negatively influence the system performance are related to their operation far from the Best Efficiency Point (BEP), which can cause cavitation phenomena, excessive vibration, recirculation of suction and discharge, wear of the equipment, reduction of efficiency and reduction of service life (Jennings, 2013). Periodic diagnostics are essential to ensure adequate performance, to reduce repair or replacement costs and the need for inspection works, as well as to carry out a more detailed and grounded analysis of energy consumption and water consumption. Two approaches can be used to carry out the diagnosis: the calculation of the simplified energy balance, developed to estimate the overall of pumping station efficiency; and the energy audits, carried out to collect further data and analyse, in detail, operation of equipment in order to identify eventual issues and to produce improvement recommendations (Santos et al., 2018). In the selection and monitoring process of an electric pump equipment, it is fundamental to ensure that the pump operates close to its rated operating conditions for the range of flow rate values in which a pump should operate (Chaurette, (2011); Budris, (2016); ANSI/HI 9.6.3-2012), which can vary between 70-80% and 110-120% of the rated flow rate. Operation outside this range leads to several operating problems, such as excessive vibration or cavitation which will accelerate degradation, reduce equipment service life, and require more intensive pump maintenance. According to Ferman (2015), for equipment of similar size to the ones analysed in this research, a pump should not operate continuously below 50% of the rated flow rate. Experience shows that most relevant reasons for pump efficiency loss are (Leite et al., 2018): i) differences between the actual operating conditions of the system, those at the time of installation and those expected in the project, based on the information provided by the manufacturer (operation under optimal conditions), and ii) expected deterioration of the equipment performance over time, contributing to the increase of energy consumption. Some of the procedures most frequently applied in pump maintenance are (Santos et al., 2018): the installation of variable speed drives to improve and adapt the operation of motors to variations in consumption; the replacement of conventional motors with others from more efficient classes; the identification of pumping systems that are operating outside the BEP; the replacement or adjustment of oversized pumps; the application of coatings in pump components, such as volutes, to reduce friction losses; the installing of an energy management system to monitor the operation of the pumping system; the regular lubrication and wear of the bearings; the regular inspection of the impeller and the seals condition. The main gaps of knowledge that have motivated this research are the following: i) lack of a robust methodology to assess energy efficiency in PS both including a simplified approach and a detailed analysis; ii) lack of a complete and well-tested set of key-performance indicators to assess PS energy efficiency, based on reference values; iii) lack of recommendations of infrastructural, operation and maintenance improvement measures according to identified inefficiencies.

3 METHODOLOGY

The methodology proposed for carrying out the energy efficiency assessment and the establishment of improvement interventions in pumping installations of water supply (WS) and waste water (WW) systems is organized in five steps: 1. Key-performance indicators establishment; 2. Data collection and KPI calculation; 3. Diagnosis and priority identification; 4. Improvement measures analysis; 5. Economic analysis.

Three categories of key-performance indicators related to the energy efficiency, technical performance and operating cost of the pumping stations are established to carry out the diagnosis (Step 1), as presented in Table 1. Necessary data for the calculation of the indicators should be collected by the WS and WW entities responsible for and organized in sets with similar characteristics and belonging to the same pumping stations (Step 2). The most relevant variables resulting from the data processing are obtained, as well as the variables included in the catalogues of each brand and model of the different PS groups. The diagnosis and identification of prioritized LI should be carried out (Step 3). This organized in three stages: i) Assessment of efficiency; ii) Identification of PS priorities for intervention; iii) Analysis of main inefficiency factors. The energy efficiency diagnosis of each PS should be carried out following a standardized procedure of performance evaluation based in the different KPI presented in Table 1. The diagnosis also aims to support decisions for the implementation of improvement measures. A comparative analysis allowed to identify the groups of LI considered to be a priority for a more detailed diagnosis, in which alternatives for intervention should be analysed (Step 4). Taking into account the performance indicators and the results obtained a list of measures designed to improve the performance of LI is drawn up, based on a selection of relevant criteria. Finally, the economic analysis is carried out (Step 5), including the calculation of lifecycle costs of a pumping station and the calculation of economic indicators.

Table 3.1 Key-performance indicators for assessing pumping stations' energy efficiency

Key-performance indicator	**Definition**	**Formula**	**Quality of service (Reference values)**
Main KPI			
Global efficiency, η_g,(%)	Global performance or efficiency is an energy efficiency indicator that permits an assessment of the quality of the EI to meet the requirements of the system.	$\eta_g = \frac{E_u}{E_c} \times 100$(3.1)	● Unsatisfactory:]0%;50%](WS) e]0%;40%](WW); ● Average:]50%;70%[(WS) e]40%;60%[(WW); ●Good: [70%;100%](WS) e [60%;100%](WW) *
Additional KPI			
Ratio of estimated and the rated discharge, Q/Q_n(%)	It is a performance indicator that is expressed by the relationship between the nominal flow rate of the pump and the actual flow rate. It allows several explanations for possible drops in performance or occurrence of degradation only with estimated and nominal flow values.		● Very unsatisfactory-: [0%; 50%]; ● Unsatisfactory -:]50%;70%]; ● Unsatisfactory +) [120%;+∞[; ● Average:]70%;90%[&]105%;120%[; ● Good: [90%;105%] *
Variation of global performance relative to optimal performance, η'_0(%)	Energy efficiency indicator that evaluates the loss of performance of each LI according to its optimal performance.	$\eta'_0 = \frac{\eta_0 - \eta_g}{\eta_0} \times 100$(3.2)	No reference values are given
Residual Life, RL	Degradation indicator, which assesses the age of LI. Values between 0 and 1.	$RL = \frac{RL - I}{RL}$(3.3)	RL of the equipment: 25 years (WS); 20 years (WW) ● Unsatisfactory: [0,0;0,2[●Average: [0,2;0,6] ● Good:]0,6;1,0]
Anual Degradation, D_a,(%/year)	Degradation indicator that allows to assess the degree of deterioration per year in the form of global performance compared to expected performance.	$D_a = \frac{\eta_e - \eta_g}{I}$(3.4)	● Unsatisfactory: [1,0:+∞[● Average: [0,3;1,0[; ●Good: [0,0;0,3[
Operation Time, t_f,(h/year)	Operating indicator that expresses the weight of energy costs, allowing the identification of the equipment that has the highest energy weight in the final invoice.		Relevant energy costs for tw:]2000; +∞[*
KPI related to energy consumption and cost			
Annual Savings, P_a,(€/ano)	Economic indicator that allows to determine the potential energy savings by comparing the global performance with the optimum of each LI, multiplied by the cost of energy (€/kWh).	$(S_a = \left(CE - \frac{E_u}{\eta_0}\right) \times C_{ue}$(3.5)	No reference values are given
Weight of Energy Cost, W_{ce} (%)	It is an economic indicator, which expresses the relationship between initial cost and energy cost	$W_{ce} = \frac{C_e}{C_{ic}}$x100 (3.6)	It pays to optimize if $W_{ce}>1$*

4 APPLICATION

4.1 Case study analysis

The proposed methodology is applied to pumping stations managed by three water supply and waste water utilities, identified herein as A, B and C. The pumping stations distributed by the three utilities are shown in Table 4.1.

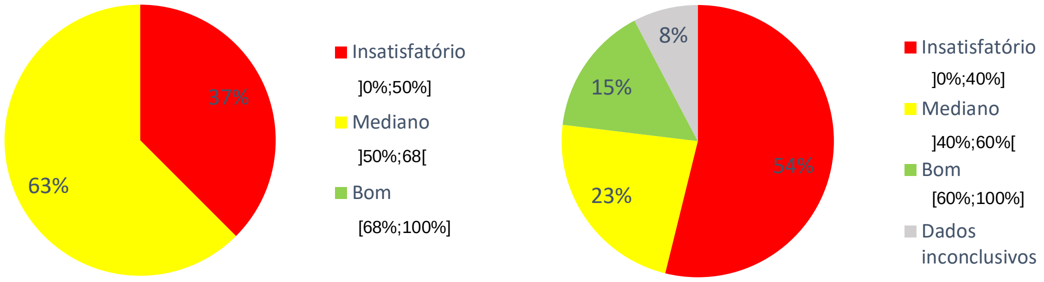
Table 4.1 Number and type of analysed pumping stations

Utilities	Pumping stations
A	8 (WS), 13 (WW)
B	37 (WS), 37 (WW)
C	77 (WS), 49 (WW)

The methodology application to the case studies allows: the diagnosis of the energy efficiency performance of the pumping station; the prioritization of PS requiring a more detailed analysis; the analysis and recommendation of energy efficiency improvement measures. Results from utility A are presented herein (Figure 4.1 and 4.2) to demonstrate the conclusions drawn.

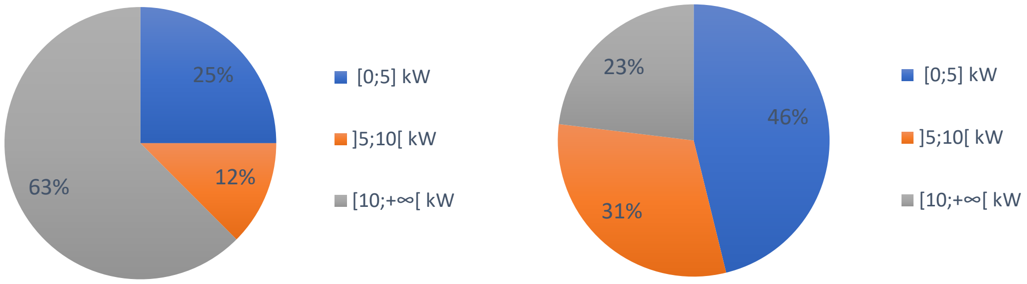
The analysis has shown that WS PS generally have higher performance levels (Figure 4.1), operating flows closer to rated levels and more reliable and consistent data than those of the WW systems. Some of the reasons for these higher performances are associated with the type of pumps used, which often represent higher investments than in the WW, as well as, have higher efficiencies at the BEP, more regular maintenance and lower friction losses in pipes and in the pump due to the liquid nature, clean water. By contrast, in WW PS, the liquid carries solid material and gases which means that the PS is significantly less efficient.

Additionally, the flow rates and the manometric heads associated with WS (Figure 4.2) are higher, and therefore, PS have higher power installed with equipment offering higher performance than in WW systems. As a consequence energy consumption is much higher in WS PS and, therefore, it is expected that utilities focus more attention on these systems and guarantee more adequate and periodic equipment maintenance. Maintenance is also more accessible in the case of WS PS as they generally are equipped with electric pumps, while the WW have, in most case, submersible groups. Data collection is also more reliable in WS PS.



(a) (b)

Figure 4.1 Energy efficiency of pumping stations of utility A: (a) WS e (b) WW.



(a) (b)

Figura 4.2 Installed power (P_1) in utility A: (a) WS e (b) WW.

The comparison of the WS PS of the three utilities shows that the PS of utility C have the best performances: 56% of the PS operate for performances between 50-68% and 10% of the PS operate with performances above 68%. The second best performing PS are from utility A and finally utility B. PS from utility C consume eight times more energy than those from utility B and thirteen times more energy than those from utility A; utility C has PS with the higher power installed, generally with higher efficiency.

The prioritization study concluded that the PS with the highest annual saving potential are those of utility C, as these consume the more energy (Table 4.2). It is also verified that, for utility A, the data provided and the existing data are not sufficient to reach the real situation diagnosis. Utility B has the highest percentage of PI with powers below 5 kW, which is one of the reasons for the worst performances. The utility B is the one with the best data record associated to the PS.

For the three utilities, in the case of WW, it is concluded that, very low efficiencies predominate, in particular for utility B, with 92% of the PS operating at global performance below 40%. The intervention measure most often requested for the three case studies is substitution or rehabilitation of the pumps. Data recording is very unreliable for the three utilities. The installed powers are relatively low and the electro-pump groups used have already performances associated with the BEP, generally, low.

Table 4.2 Priority WS pumping stations of utility C.

Pumping station	**P_1 (kW)**	**t_f>2000 (h/year)**	**Energy cons. (%)**	**η_g (%)**	**Q/Qn (%)**	**VR(-)**	**D_a (%/year)**	**η'_0 (%)**	**P_p (€)**	**Priority**
Water supply system										
5.2(3+1)	180	Yes	12,1	58.0 🟡	97.5 🟢	0.3 🔴	0.3 🟢	15.4	11869.1	1
4.4(1+1)	83	Yes	6,1	61.9 🟡	95.0 🟢	0.5 🟡	1.5 🔴	23.6	9230.3	2
6.6(1)	24	Yes	3,7	44.9 🔴	86.6 🟡	0.5 🟡	1.1 🔴	29.8	7143.8	3
6.2(2+1)	41	Yes	2,9	54.1 🟡	104.8🟢	0.4 🟡	0.5 🟡	24.9	4670.4	4
6.3(1+1)	33	Yes	3,6	57.5 🟡	80.0 🟡	0.4 🟡	0.6 🟡	17.8	4073.8	5

4.2 Replacement of PS 5.2 from utility C

An example of the improvement measure “replacement of the pumping groups” is presented herein. The PS 5.2 is selected has it has the highest potential for savings and is, therefore, the first priority (Table 2.1). Several solutions are analysed for pumping station (Table 4.3), considering different configurations and pump manufacturers. The solutions that most quickly compensate their investment value are 1.2 and 2.2, consisting of centrifugal pumps with vertical axis that operate alone, in a "1+0" type configuration. However, knowing that this is a very important IE for consumers, it will be unthinkable in the event of a failure that the operation is interrupted, thus opting for the same solution, but with a safety pump, i.e. 1.3.

Table 4.3 Analysed solutions for the replacement of PS 5.2

Solutions	Layout	Brand and model	Size	$\eta_{expected}$(%)	Variable speed drive	Q/Qn (%)	Efficiency improvement (%)
1.1	“1+0”	KSB, Etanorm	80-65-315	68 🟡	No	87🟡	10
1.2	“1+0”	KSB, Movitec	125	73🟢	Yes	93🟡	15
1.3	“1+1”	KSB, Movitec	125	73🟢	Yes	93🟡	15
1.4	“2+0”	KSB, Movitec	90	69🟡	Yes	75🟡	11
1.5	“2+1”	KSB, Movitec	90	69🟡	Yes	75🟡	11
2.1	“1+0”	Grundfos, NK	65-315	66🟡	Yes	78🟡	8
2.2	“1+0”	Grundfos, CR	185-4-3	76🟢	Yes	85🟡	18

5 ENERGY EFFICIENCY MAIN FACTORS

The factors that most affect the energy efficiency performance of are analysed. Results refer to the analysis of all the pumping stations – 122 PS of water supply systems and 99 PS of waste water systems – organized in two sets: the first presents the PS of WS systems and the second the PS of WW systems.

The efficiency depends on several analysed factors. For the water supply, PS systems are mostly composed of pumping stations with installed power higher than 10 kW, energy consumption also higher in this range and more efficient performance evaluations. The most frequent efficiency assessment is the “average” (between 50% and 68%) which indicates that, at a general level, the performance is acceptable, however, the "good" rating (higher than 68%) is rare, which leads to the conclusion that there is still a very high potential for improvement. The Q/Qn indicator prove, to be very useful for the analysis and it highlight the fact that PS with higher installed power have better efficiencies. It was also evident that the flow rate in these PS is generally closer to the rated conditions. The opposite is observed in PS with lower installed power, in which most PS are oversized (Figure 5.1); also, a high percentage of PS are operating at the end of their service life. In general the analysed data are considered to be reliable.

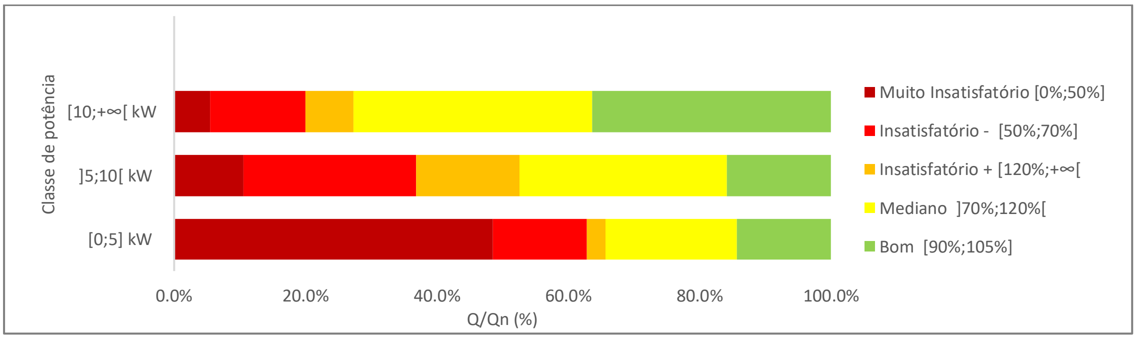


Figure 5.1 Distribution of WS PS by performance level in each Q/Qn for each installed power category

For wastewater systems, it was identified a predominance of PS with lower installed powers, below 5 kW. As in the case of the WS, the highest energy consumption are verified in PS with higher installed power (over 10 kW). Most of the verified energy consumption is associated with PS operating at "unsatisfactory" efficiency performance levels (between 0 and 40%). The most frequently efficiency performance levels is "unsatisfactory". The Q/Qn sizing is very illustrative of the poor performance of PS performance, which operate, most of the time, far from the rated conditions, below 50% of Qn. It can, therefore, be concluded that there is a great need for improvement in terms of energy loss reduction. In this case the analysis is affected by low reliability of the provided data, which did not allow improvement solutions proposals.

6 CONCLUSIONS

The results of the analysis led to the conclusion that the proposed methodology is useful and adequate to carry out a diagnosis of the operation of PS without the need of energy audits. The efficiency indicators adopted have proven to be useful, as they allow to identify, through simple calculations, which PS are the most inefficient and require a more detailed assessment. The complementary indicators have also proven to be very useful highlighting, in particular: the ratio between the estimated discharge and rated discharge (Q/Qn), the variation in global performance relative to optimal performance, the residual life, the annual degradation and the annual operating time. The the ratio between the estimated discharge and rated discharge have proven to be the most relevant complementary indicator, as it was possible, in most cases, to determine the reasons why efficiency varied positively or negatively. Finally, consumption indicators, such as annual savings and the weight of energy cost, have shown to be useful in determining the potential for energy savings and the relationship between the weight of the initial cost and the energy cost. It can be concluded that higher power PS are generally better sized (i.e. the operating discharge is close to the rated discharge), have better efficiencies, longer service lives, higher maintenance care and are also the most energy consuming PS.

Finally, PS data from supply water systems is much more consistent than data from wastewater systems, with less failures and lower associated uncertainties, with better record of operation data. The PS of supply water systems had more stable operating times, more efficient pumping groups and more regular maintenance. Wastewater PS generally had equipment operating far from the BEP and were typically oversized; little reliability was also found in the data relating to WW systems, particularly for PS with lower installed power.

7 REFERENCES

Santos, A., Oliveira, F., Soares, G., Carneiro, J., Lima, L., Viegas, M., Corigo, P., Nogueira, P., Cardoso, P. e Quaresma, P. (2018). Guia 24-Uso Eficiente de Energia nos Serviços de Águas. Lisboa: Entidade R. http://www.ersar.pt/pt/publicacoes/publicacoes-tecnicas/guias

Stoffel, B. (2015). Assessing the Energy Efficiency of Pumps and Pump Units: Background and Methodology. Amsterdam: Elsevier. https://doi.org/10.1016/C2014-0-04677-1.

Heinz, P. B. e Budris, A. R. (2015). Pump Users Handbook. https://doi.org/10.1017/CBO9781107415324.004.

Jennings, B. (2013). Some Effects of Operating Pumps Away from Best Efficiency Point. Hydro inc, feb.2013. https://empoweringpumps.com/some-effects-of-operating-pumps-away-from-best-efficiency-point/

Budris, A. R. (2016). *Centrifugal Pump Flow Operating Regions and Impact on Reliability*. Water World, set.2016. https://img.waterworld.com/files/base/ebm/ww/image/2016/09/1609wwpmp_z03.png?auto=format&fit=crop&h=720&w=1280.

Chaurette, J. (2011). *Guidelines For Pump System Designers*. Plant Engineering. Illinois. https://www.pumpfundamentals.com/download-free/guideline_pump_system.pdf.

Ferman, R. (2015). What is the purpose of minimum flow?. Pump Industry, dec.2015. https://www.pumpindustry.com.au/what-is-the-purpose-of-minimum-flow