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ENERGY EFFICIENCY MEASURES IN ELETRIC MOTORS FOR WATER SUPPLY SYSTEMS

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Abstract

The increase of water and electric consumption has caused concerns in relation to scarcity and water stress, while stimulating the development of energy efficiency techniques in water supply systems. However, these techniques can be considered costly and complex, since they use computational equipment and tools that make it difficult to implement into operational practice. In this regard, especially in developing countries, there is a need for progress in energy efficiency measures with low economic dependence on both equipment and tools, guaranteeing necessary environmental and social benefits. This study evaluated energy efficiency measures in a water supply system through the use of (i) a frequency inverter and (ii) replacing the electric motor with a more efficient motor. The first measure did not show economic attractiveness, revealing that frequency inverters do not always have applicability in reducing energy costs. However, the necessity of a soft starter should be noted, as well as suggested studies that have changes in the operating system that can make this measure attractive. The second measure demonstrated economic potential and reinforced the importance of commercial availability and technical regulation of high-efficiency motors, since the payback period was 4 years, with application potential throughout the water supply system.

Keywords: hydro energy efficiency, high-performance motor, operational control, frequency inverter.

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Introduction

The technological, industrial and populational expansion promotes an increase in water and energy consumption, while demonstrating the need for continued expansion and improvement of existing water supply systems (WSS) (Ramos *et al*., 2010; Bolognesi *et al*., 2014). Water stress, climate change issues and economic risks stemming from market instability have contributed to the development of efficient water management methods. In this sense, case studies involving life cycle assessments (LCA) on WSS management and its environmental impacts have shown great importance for seeking and taking efficient measures (Boulay and Lathuillière, 2017).

Techniques aiming at reducing costs with electric energy in WSS such as optimizing reservoirs (Batchabani and Fuamba, 2014; Fang *et al*., 2010; Hallmann and Suhl, 2016), pumping control (Georgescu *et al*., 2014) and developing computational models (Diniz *et al*., 2015) have evolved and shown potential for the conservation of hydroenergetic resources.

Developing countries, however, still find structural obstacles, such as inadequate distribution system management (Mohammed and Sahabo, 2015) and, consequently, the issue of water loss (Dighade *et al*., 2014). In addition, socioeconomic problems, such as the lack of investment in basic sanitation, (WWAP, 2014), make it difficult to apply such studies.

The development of more practical assessments (Monteiro and Monachesi, 2005), compared to works with complex computational tools (Vamvakeridou-Lyroudia *et al*., 2007), to reduce energy costs in water supply systems can contribute to the fight against the lack of economic availability and support for research, especially in emerging countries.

Research developed in this work used diagnostic techniques to analyze monitoring data from a part of a WSS and operational control, aiming to propose and evaluate energy efficiency measures. The proposals of installing a frequency inverter and changing the electric motor to a high-efficiency model were examined. With a reduced demand for computer equipment and tools, this research favors applications in developing countries, highlights the potential of energy efficiency studies in WSS and contributes to environmental issues.

Energy Cost Reduction Techniques

Operational efficiency makes the operation of the WSS parts compatible with the objective of harnessing its potential. Fang *et al*. (2010) and Georgescu *et al*. (2014) demonstrate the possibilities of optimization and operational adequacy through research involving reservoirs and pumping controls.

In the same field, the use of frequency inverters have presented applications not only in water supply systems as the main measure for flow control (Kaya *et al*., 2008), but also in electric motors used for heating, cooling and air compression (Saidur *et al*., 2012). The application of frequency inverters demonstrate the possibility of reducing costs, as they modify electric motor rotation speed by changing its characteristic curve and making the operation more suitable for loading (Luo *et al*., 2015).

According to studies by the IEA, International Energy Agency (2011), global electricity consumption has a 40% contribution from electric motors. However, this research includes several uses of this equipment, in addition to WSS, industrial use is included, which has significant contributions. On the other hand, research development for energy conservation in electric motors for water pumping shows a field with high economic return potential (Kaya *et al*., 2008).

The necessity to conserve natural resources, reduce greenhouse gas emissions (UNFCCC, 1998) and use efficient energy promoted the development of high-efficiency parameters for electric motors (Lu, 2016). The results using high-efficiency motors show technical and economic attractiveness, taking into account electric power reduction and operational gain (Kaya *et al*., 2002).

The standardization of efficiency levels for electric motors such as the United States' NEMA (National Electrical Manufacturers Association) and the European Union's IEC (International Electrotechnical Commission) has been adopted by developed and developing countries. These specifications deal with the maximum levels of loss that electric motors can present, speed control, installation and maintenance safety (Lukaszczyk, 2014).

Brazil also follows the IEC standardization through ABNT NBR 17094-1: 2018- Rotating Electric Machines: Induction Motors, which considers minimum performance indexes according to power. This measure has a special effect on industry (Geller *et al*., 2004), however there are also market restrictions for specific uses in supply systems.

Even with normative support, energy efficiency practice in the Brazilian water and sanitation sector is sometimes neglected, since the initiatives are mainly focused on combating losses and universal access to water and sewage services (Brasil, 2016). As in other developing countries, there is a need to meet increasing water demand and problems related to WSS infrastructure through the use of available resources and simplified tools (Mutikanga *et al*., 2009).

Materials and methods

This study is a diagnostic analysis of the supply system, which required studies on the operational control and pumping system (Figure 1). This analysis led the research to the area of energy cost reduction through changes in the operating system with (i) frequency inverters and (ii) replacing the current electric motor with a high-efficiency model. Both proposals were analyzed technically and economically.

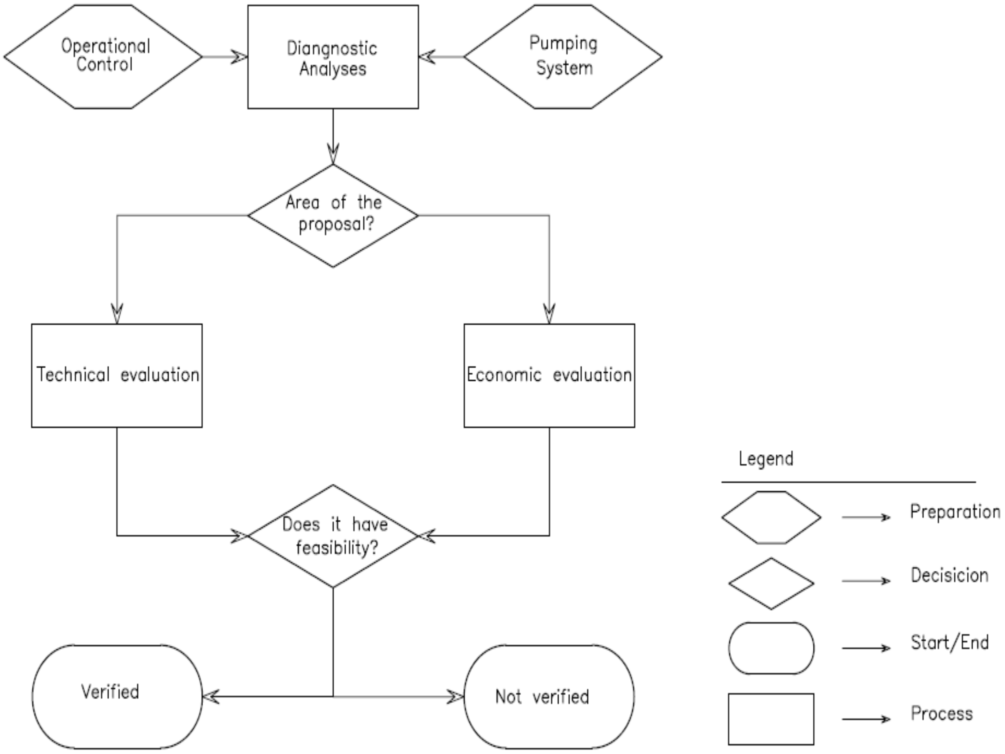

Figure 1. Materials and methods flowchart.

Research area

The José Abrão water supply system (WSS) is located in the Central-West region of Brazil, with an underground collection of the Serra Geral aquifer, the most exploited aquifer for economic and supply purposes in the city of Campo Grande. The water produced, about 839 $m^3 d^{-1}$, is destined to residential and commercial areas and to the State University of Mato Grosso do Sul (UEMS). The average consumption per inhabitant is 179 $L.hab^{-1} d^{-1}$. This value is higher than the values in the region of this study where the average consumption is 144 $L.hab^{-1} d^{-1}$ (Brasil, 2016).

In the region of this study, about 50% of the water supply is from underground wells with a tendency to increase due to expansion plans. The water is abstracted by a submerged pump and is sent to an elevated reservoir with a 100 m^3 capacity, where it receives simplified treatment by means of chlorination.

The water is distributed by gravitational potential difference, without pressurized equipment in the network, which is approximately 8 *km* in length. Figure 2 represents the location and hydraulic model of the research area.

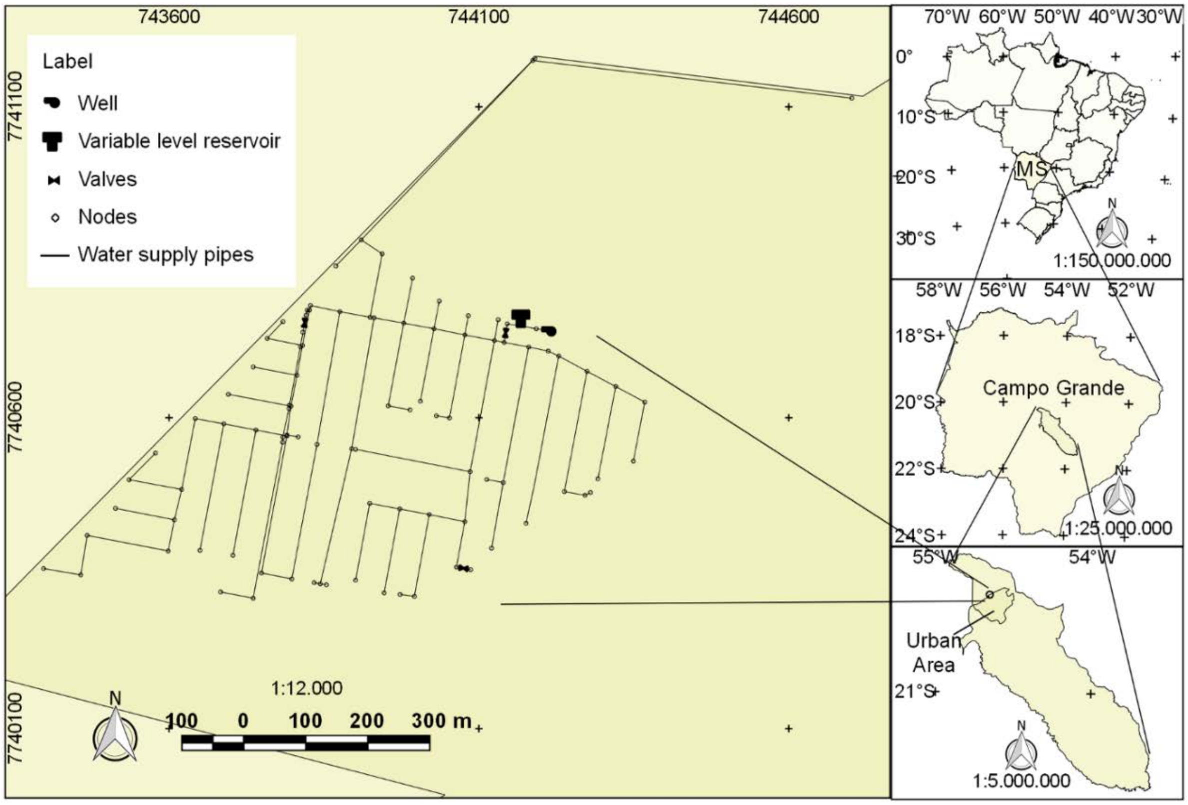

Figure 2. Location and hydraulic model of the research area.

The pumping system consists of a submersible pump from the manufacturer Ebara®, with a national distributor, whose characteristics are presented in Table 1. The operation is automated and controlled by an Operational Control Center (OCC) following contracted electric plan guidelines and the reservoir's operational limits.

During higher tariffs, between 17:00 and 21:00 pumping is avoided, the minimum reserved volume being 50 m^3 and during the other periods 80 m^3. These parameters are used to power the pump. Electric tariffs are green hourly, with a fixed electric demand and different collection rates throughout the day (Table 2). Pump stoppage does not only happen during maintenance or water supply emergency situations.

Table 1. Features of the submerged pump

Model	Power	Flow rate	Manometric head	nº of stages	Rotation
	kW	$m^3.h^{-1}$	mwc		Hz
EBARA BHS 517-7	18.60	75	64	7	60

Note: mwc – meters of water column
Source: Ebara® (2020).

Table 2. Seasonal green hourly billing system.

Electrical demand ($US\$.kW^{-1}$)	Consumption ($US\$.kWh^{-1}$)	
Peak/Off-peak	Peak	Off-peak
3.13	0.31	0.06

Models and data

Information from José Abrão WSS was provided by the municipal supply concessionaire, such as the CAD system’s physical and commercial data, the Epanet software hydraulic model and also the registered text documents. This information refers to monitoring parameters such as distribution flow, measured consumption, reservoir level variation, electric bills and installation and operating characteristics of the pumping system.

Diagnostic analysis

The reservoir and pumping system operations were analyzed through relationship diagrams for the manometric head and flow, the electric energy consumed and time it was used, as well as physical characteristics: volumetric capacity, reservoir operating height, operating point and electric pump switchboard.

This study was led to cost reduction by altering the operating system, since the José Abrão WSS has discontinuous pumping and a fixed flow point (Figure 3); and also, by reducing electric energy consumption, since the efficiency of the motor pump assembly operates below recommended standards (Table 3).

Cost reduction through operating system change

The feasibility study of the frequency inverter installation was carried out by modeling the pump’s characteristic curve under different rotations according to Equations 1, 2 and 3; which correlates hydraulic parameters (Porto, 2006).

$$\frac{Q1}{Q2} = \frac{N1}{N2}$$ **Equation (1)**

$$\frac{H1}{H2} = \left(\frac{N1}{N2}\right)^2$$ **Equation (2)**

$$\frac{P1}{P2} = \left(\frac{N1}{N2}\right)^3$$ **Equation (3)**

Where
Q: Flow
H: Head
N: Rotation frequency
P: Potency

It was then verified whether the modifications in the characteristic curve of the pump motor assembly would meet the minimum flow and head requirements required by the system.

Cost reduction by reducing electric energy consumption

The proposal to reduce the electric energy consumption by replacing the electric motor with a high-efficiency model was based on the hypothesis that the new motor would operate under the same operational control conditions, range and engine operating time currently installed. This activity was divided into three stages: (I) determining electrical power consumed by the new engine; (II) quantifying the operating time of the present motor and (III) calculating the energy consumption with the change.

The potency consumed by the high-efficiency motor *(HP)* was calculated theoretically by applying Equation 4.

$$HP = \frac{\gamma x Q x H}{\eta}$$ **Equation (4)**

Where
HP: High efficiency motor potency
Q: Flow
γ: Specific weight of water
H: Head
η: Pump assembly efficiency

The current operating time (t) of the pumping system, as well as the proposed new high-efficiency system, were estimated through Equation 5 (Monteiro and Monachesi, 2005). The electric energy used was provided by the manufacturer of the equipment and the energy consumption *(Ec)* was obtained through electric energy bills.

$$E_c = Pxt \rightarrow t = \frac{E_c}{P}$$ **Equation (5)**

Where
t: Operating time
P: Potency
$\mathrm{E_c}$: Energy consumption

The estimated nominal efficiency of the new engine was obtained by consulting the Brazilian standardization ABNT NBR 17094-1: 2018 (ABNT, 2018), which establishes minimum yields according to *HP* (Table 3). In the case study the yield was 91% since the reference power was 18.5 *kW*.

Table 3. Minimum yield according to ABNT NBR 17094-1: 2018.

Nominal power		Synchronous speed (Hz)	
cv	kW	60	30
		Nominal yield (%)	
15.00	11.00	90.20	91.00
20.00	15.00	90.20	91.00
25.00	18.50	91.00	92.40
30.00	22.00	91.00	92.40
40.00	30.00	91.70	93.00

Economic viability of energy efficiency measures

The economic viability method used was the minimum theoretical pay-back period (MTPB) according to Chazarra *et al*. (2018). MTPB represents the minimum number of months in which the investment costs are expected to be recovered, without considering the time value of money. MTPB was estimated from the monthly maximum theoretical income (MTI) and the investment costs.

In the economic viability calculation, MTI was obtained throw the theoretical comparison of the energetic cost between the current electric motor and the high-efficiency model. Both equipments would work at the same control rules and period, the difference is in the yield of each one. The investment cost includes the acquisition of the high-efficiency motor and the cost of installation and preventive maintenance.

A survey of the cost of the equipment and its maintenance was carried out through research with suppliers. However, since only standard submersible pump engines were found, the cost was estimated according to Freitas *et al*. (2008) where the recommendation is to use the average price of standard line engines with a 30% increase. The installation cost used was the value recommended by the National System of Prices and Indices for Civil Construction (SINAPI).

Results and discussion

Operating system change via frequency inverter

The applicability of frequency inverters was evaluated by the flow and manometric pressure demanded by the system, as represented in Figure 3, since modifications in the rotation speed did not affect the minimum requirements of these two factors (Fang *et al*., 2010). According to the data of the case study, with a geometric difference of 57 *mwc*, the gauge pressure was the point of restriction.

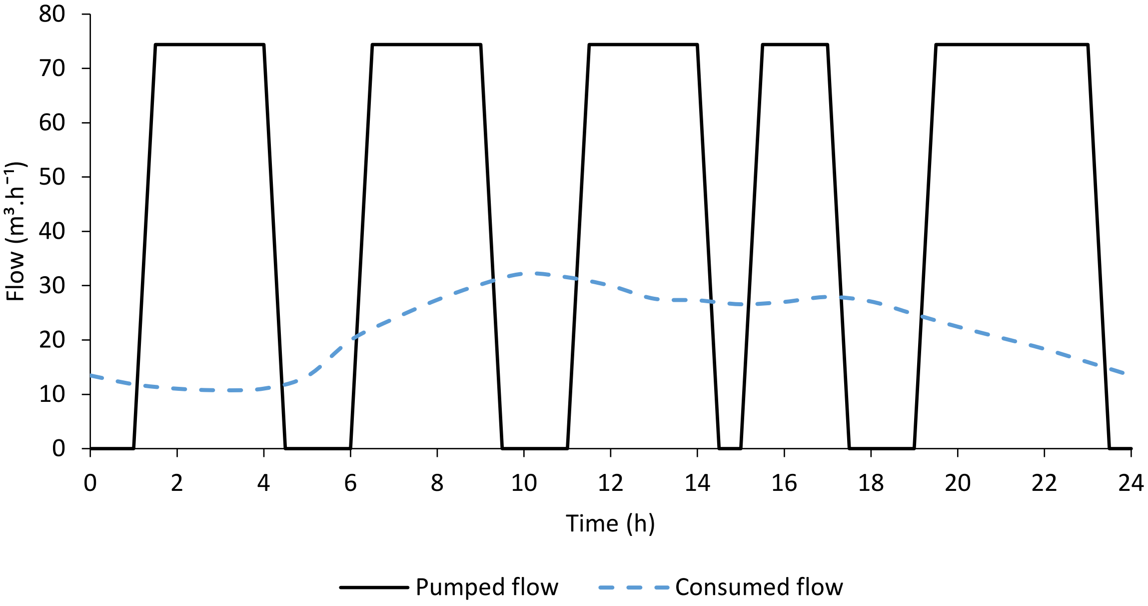

Figure 3. Flow curves consumed and produced

The operation of the direct starting pump system, i.e., without a speed control device, contributes to a reduced pump life and also to the occurrence of peaks in the electrical power demand (Hydraulic Institute *et al*., 2004). In addition, the water balance between produced and consumed flows are not the same, which is another important factor. This is because the volume of water produced is 930 $m^3.d^{-1}$ and the volume consumed is 546 $m^3.d^{-1}$, which means that there is a water loss of 41%, very close to the average water loss in the studied region, which is 39.8% (Brasil, 2016). Even though the analysis was performed in an approximate manner, without using a Water Balance Matrix (Mutikanga *et al*., 2013); the result is not invalid, and shows waste in existing hydropower resources.

Simulations using the frequency inverter with characteristic curve modifications of the motor pump set for 45 and 30 *Hz* rotations are shown in Figure 4.

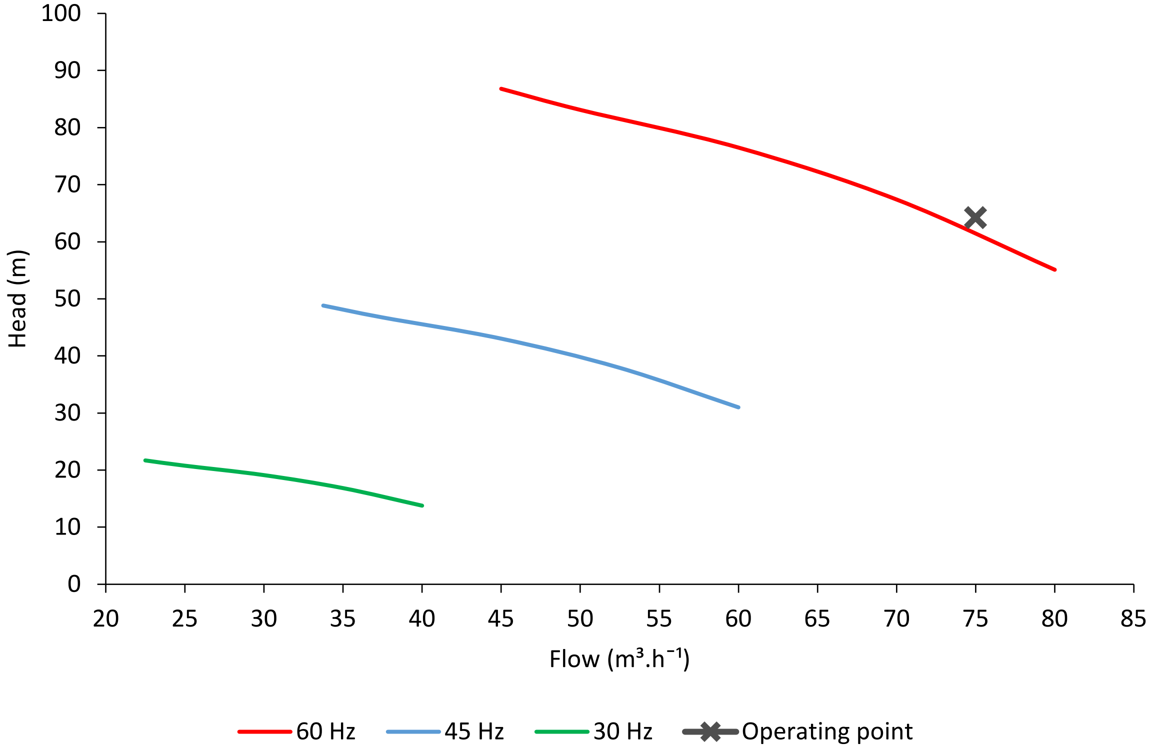

Figure 4. Curves of the pumping system for different rotations.

Although the reduced pump rotor frequency can meet the José Abrão WSS' water requirements, the minimum manometric head is not achieved, which makes the pumping system operation impossible for the specified rotations. However, similar case studies, with more flexible operating requirements, have shown technical feasibility (Saidur *et al*., 2012).

On the other hand, the direct starter electric power system, has no restrictions for installing the soft starter softening device. Its use can reduce corrective maintenance frequency in the electromechanical components of the motor pump assembly and avoid water hammer (Greenwood, 2015).

Even with the mentioned benefits, the economic evaluation of installing a soft starter device is not widespread in literature. No case studies were found that indicate reduced maintenance costs or even reduced fines with contracted electric plans when the electric demand is exceeded. The justification of its use is, therefore, the protection it offers to the electromechanical components.

In relation to water losses, there is a need for studies about combat plans and also operational control so that pumping and reservoir systems are integrated. The possibility of having the pump turn on for different water levels must be checked to reduce working time and/or the number of times it is turned on, operating in a less interrupted manner.

Eletric motor replacement

The operating time of the electric motor between January to October 2016 (Table 4) was found from Equation 5 and was used as a reference for the estimated economy with installing the high-efficiency motor.

Table 4. Estimated operating times throughout 2016.

Month	Peak consumption (kWh)	Off-peak consumption (kWh)	Demand (kW)	Peak time (h)	Off-peak time (h)
Jan	1,031.00	7,102.00	349.86	55.31	381.01
Feb	868.00	7,896.00	349.86	46.57	423.61
Mar	1,019.00	6,825.00	349.86	54.67	366.15
Apr	607.00	7,685.00	349.86	32.56	412.29
May	517.00	7,859.00	349.86	27.74	421.62
Jun	533.00	7,585.00	349.86	28.59	406.92
Jul	550.00	7,224.00	349.86	29.51	387.55
Aug	669.00	7,774.00	349.86	35.89	417.06
Sep	647.00	8,017.00	349.86	34.71	430.10
Oct	665.00	7,605.00	349.86	35.68	407.99

Figure 5 shows the differences between the energy costs that reached approximately 20%. Measures such as these, related to the WSS management, do not have an isolated repercussion, since they are integrated with environmental issues generating impacts such as the reduction of greenhouse gas emissions (Lu, 2016). In this sense, in addition to the importance of the case studies to evaluate economic impacts, it is suggested that environmental impacts are also quantified (Fantin *et al*., 2014), including ecological and water footprints.

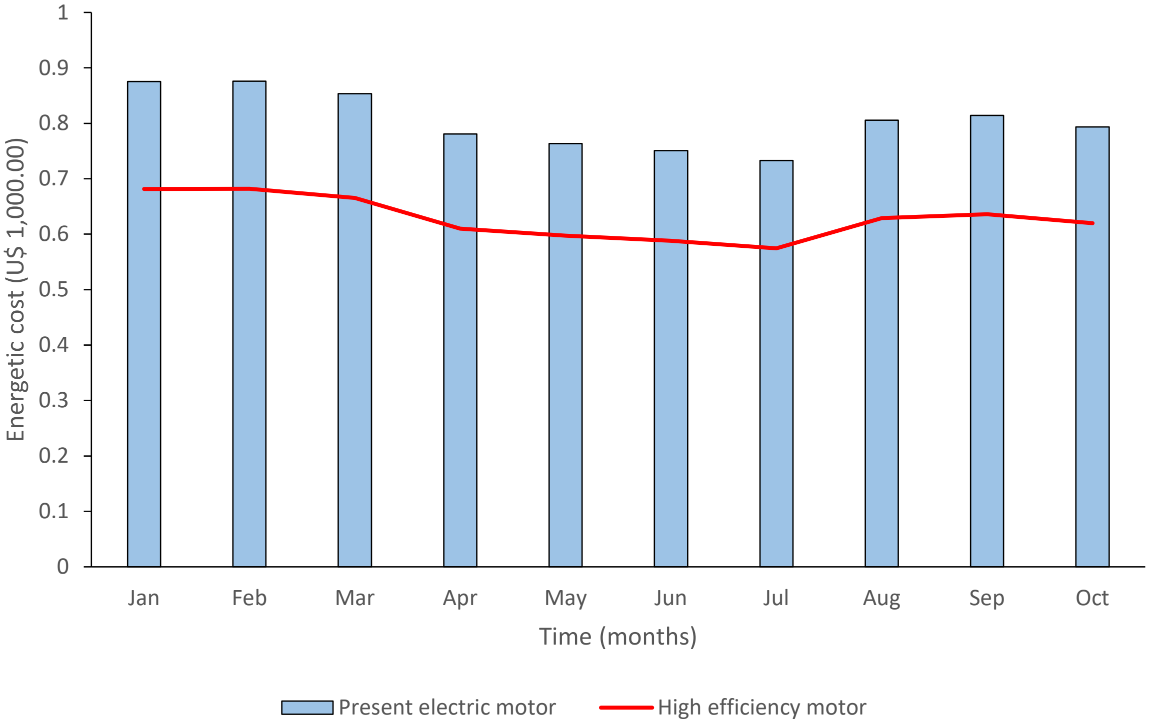

Figure 5. Comparison of energy consumption between electric motors.

Since electricity costs are the most representative in pumping systems (Hydraulic Institute *et al*., 2001), its reduction consists of the factor with the main economic return due to the exchange of electric motors, with a payback period of 48 months (Table 5). This is considered attractive since the life of a submerged engine pump system is about 25 years according to the manufacturer. If the economic benefit of the motor replacement was counted, without the initial 4 years of self-payment, it could generate an economic equivalent of purchasing 10 standard electric motors or around *US$* 50,400.00.

In addition, economic feasibility studies such as the one presented in this paper point to economic attractiveness, but have varying payback periods (Kaya *et al*., 2008), which depend mainly on the number of hours the device was turned on, local electricity tariffs and the investment cost. Therefore, each case must have an appropriate economic evaluation.

Table 5. Calculation of economic parameters

Power (kW)	Power (kW)	Energy consumption reduction (kW)	Monthly operation (h)	Investment (US$)	Monthly net benefit (US$)	Return on Investment (months)
Electric Motor	High-efficiency Motor					
18.75	14.02	2040	444	8,553.49	176.15	48

Even if economic attractiveness is proven, the Brazilian standard ABNT NBR 17094-1: 2018 does not cover electric motors designed for submersible pumps like standards in other countries such as Europe (IEC, 2014) and Japan (JIS C, 2014). The lack of efficiency regulations causes the market to be unattractive for producing such equipment and, consequently, it is technically unfeasible.

Conclusion

The diagnostic analysis of this study technically and economically evaluated efficient energy alternatives by changing the operating system by using a frequency inverter and replacing the electric motor with a high-efficiency model.

Using a frequency inverter in this case study was not feasible, since the manometric head demanded by the WSS was not achieved. However, installing a soft starter device in the electrical starting system in order to extend the life of the motor pump assembly and to extend the corrective maintenance period is suggested. In addition, it is necessary to study other ways of changing the pump and reservoir’s operating system in order to decrease how many times the pump is turned on and water stress.

Since there are water losses of 41%, even if obtained in a simplified way, the need to have a plan that is executed to combat losses is evident, thus reducing hydroenergy resource waste and once again water stress in the Serra Geral aquifer.

The replacement of the current electric motor by a high-efficiency model has significant economic attractiveness, since the payback period of the investment from the reduced energy costs occurs in approximately 4 years. In addition, there is an opportunity to regulate this type of motor for submersible pumps and consequently become commercially available, since they are not yet considered in the region of this study.

The economic evaluation of using the high-efficiency motor should consider the possibility of renegotiating the contracted tariff, since the electric demand can be reduced. However, the commercial unavailability of such engines in the region studied prevented this quantification, which could reduce the payback period of the investment.

Even if the economic potential for energy efficiency measures is verified, case studies, such as this one, should also take into account the feasibility analysis of their implementation and possible environmental benefits triggered such as the reduction of greenhouse gas emissions and preserving natural resources (Herstein *et al*., 2009), considering the potential of reducing environmental impacts with the adequate energy efficiency measures in electric motors for WSS management.

A monthly benefit of *US$* 176.15 can be considered small when compared to total energy expenditure in the same period, however, the application of this case study to other regions may present even more significant results. Mainly because the study was in a water supply subsystem, which represents only 1% of every urban area that the measure could be applied.
The research approach, as it does not demand complex computational tools and contemplates accessible diagnostic analyzes, assists in the application of energy efficiency projects in countries or regions lacking technical and economic resources in the water and sanitation sector.

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