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Assessment of Energy Efficiency in Pump Stations of Pressurized Irrigation Systems (Case Study: Qazvin and Kermanshah Provinces)

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Abstract

About 20% of global electricity production is consumed in rotary equipment to convey fluids such as water, gas, air, and other liquids, while the loss of energy consumption in this sector is more than 60%. The aim of this study was to evaluate different efficiencies in the pumping stations in the pressurized irrigation systems to address low energy efficiency issues in the pump stations and to develop solutions to enhance it. In this regard, the electrical efficiency, hydraulic efficiency, and mechanical efficiency were determined in the studied pump stations and they were used to determine total efficiency of each pump station. Pump station assessment tool (PSAT) software was used to model each station and predict annual energy consumption costs; furthermore, the potential of efficiency improvement was calculated. Results showed that the total efficiency of the studied pump stations ranged from 13 to 32% and averaged 24%. Factors, such as improper design, disproportion in terms of the operation conditions, and the design and improper operation, caused a drop in the efficiency of the pump stations. Also, the productivity of the energy consumption in the pump stations can be improved from 24 to 49% if these issues are tackled.

Keywords:
Electro-pump efficiency, hydraulic efficiency, mechanical efficiency, design capacity, energy productivity, PSAT

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INTRODUCTION

Today, energy is known as one of the main factors limiting the development of agricultural and industrial activities in the world. Environmental issues, non-renewable fossil fuels, and restrictions on public use of other energy sources, including nuclear energy, render clean energy and efficiency increasingly noticeable. Water pumping stations are one of the major energy consumers that should be considered. Given the growing trend of energy prices, it is imperative to develop methods and tools aimed at reducing energy consumption, alleviating environmental impact, and enhancing economic benefits. However, the share of energy consumption in the irrigation sector is not as considerable as that in the industrial sector and urban activities, but the share of energy costs in the irrigation sector is one of the main inputs to this section, so the development of modern methods of irrigation, e.g., drip irrigation, increases energy consumption.

Energy costs in the water economics are very important because about 70% of the total electricity production of the world is consumed by pumps, compressors, and fans, out of which about 20% is consumed in pumps. This is despite the fact that energy loss in pumps is over 50%.

Due to lack of regulations and technical specifications for equipment used in pumping stations and disregard for scientific planning and expertise to optimize the use of energy, energy loss is increasing, and consequently, the pump station equipment depreciation is increasing. Selecting inappropriate electro-pumps in the pump station designing stage, changing operating conditions, reducing system performance over time, and changing hydraulic system pump can impair pump efficiency and ultimately affect the entire pumping system. Inappropriate electro-pump selection and inattention to the actual energy need of the system, using electro-motors with high power, electro-motor and pump mismatch, and lack of energy load management could increase energy consumption, and consequently, increase the costs in the pump stations.

Due to technical issues and design requirements, pump selection should be correctly and properly in accordance with the design and operation of pump stations which are practical ways to help improve the situation (Yates & Maurice, 2006). In this research, the average total efficiency was determined to be 46.6 and 12.7% for electrical and diesel pump stations, respectively. Factors affecting efficiency are depreciation of motor and pump, using the pump or motor with inappropriate capacity, and improper installation of pump station equipment (Rezvani et al., 2010). In another study, the average efficiency of pump station for water supply was 38.2%; for a solid set, sprinkler irrigation system with a covered area of more than 20 ha, it was 41.7% and 15.5% with direct and indirect pumping, respectively; for a solid set, sprinkler irrigation system with a covered area of less than 20 ha, it was 38 and 14.5% with direct and indirect pumping, respectively (Amanlou et al., 2011). Pump stations in Kansas (USA) consume 40% more fuel than the required level because of improper pump selection, pump wear, incorrect size of electro-pump, and wrong connection of electro-motor and pump (Rogers & Alam, 1993). In evaluating 25 districts of Texas, the minimum, maximum, and average efficiency of pump station were 17.5, 68.5, and 42.6%, respectively (Fippes & Neal, 1995). In another research which was conducted in Fars Province (Iran), energy loss in pump stations was very high. The most important causes of energy loss were the fatigue of electro-pump and mechanical equipment, improper sealing of fittings, and the lack of the use of maximum power of electro-motors (Amin & Sepaskhah, 1996).

According to New (1986), the efficiency can be 75 to 82% for pumps, and it can be 75-85% and 85-92% for small and big electro-motors, respectively. Therefore, it is recommended that, if possible, a large electro-pump be used instead of several small electro-pumps (Zabihian & Amanlou, 2013). For pumping water, it is suggested to consider crop water requirement, evaluate and modify irrigation systems, estimate current pump efficiency, and manage the amount of consumed electricity to reduce energy consumption (Hill, 1999).

In Iran, optimization of pump stations would save annually over 6.44×109 kWh for the country's economy (Shayesteh, 2010). The results of the research showed that perfect planning for the operation of pump stations is indicative of careful monitoring of pump stations which can reduce the energy consumption by about 6 to 8.4% (Reynolds & Bunn, 2010). On the other hand, equipping pump stations with speed control system, in addition to reducing energy consumption, can lead to a decrease in depreciation of mechanical equipment, such as valves (Liu & Xi, 2012). A substantial percentage of the operation cost is due to energy cost in pump stations and the main reason for this high cost is the lack of an optimal pattern for the pressure supply in the network (Bohórquez et al., 2015).

So far, pump station performance has been neglected in the evaluation of irrigation and drainage networks, whereas any disruption in pump station would lead to dysfunction of the irrigation and drainage networks. Due to the increasing development of pressurized irrigation systems in Iran and the certainty of reducing subsidies allocated to the agricultural sector in the near future, it is imperative to evaluate and optimize energy consumption in pump stations. The final results of such evaluations could be diagnosis and classification of problems and help to improve pump station performance as well as to improve pump station operation (Reynolds & Bunn, 2010).

Increasing energy efficiency in agricultural water pump stations that supply most of the water needed for irrigation and drainage networks in Iran is of crucial importance. To produce 1 kWh energy, a gas-fired power plant emits 440-780 g CO_2 into the environment (Weisser, 2007). So, it is essential to adopt pertinent measures to reduce energy consumption, minimize environmental impact, and enhance economic profit. A great deal of electricity in Iran is generated by gas-fired power plants. Therefore, optimizing energy consumption in pump stations could make a significant contribution to the alleviation of environmental pollution.

Despite high energy consumption of pumps, there has been very little research on the efficiency of pump stations and the ways to improve their efficiency through field studies in accordance with model simulations so far. Although much work has been done to date in the world but not in Iran. So, more studies need to be conducted in Iran to evaluate the energy efficiency in pump stations of pressurized irrigation systems and find an appropriate technique to improve energy efficiency in irrigation systems in two provinces as representative examples. This subject matter was found to be of importance to decision-makers in providing them with the necessary background to adopt the right policies. This study surveys pump stations supplying water for pressurized irrigation systems in Qazvin and Kermanshah provinces and seeks to find ways to achieve the optimal situation using the Pumping System Assessment Tool (PSAT) software package (PSAT, 2000). Those two provinces were selected because they were available and representative.

METHODOLOGY

The present study was conducted on the pump stations of pressurized irrigation systems in farms and orchards of Qazvin and Kermanshah provinces in 2013 and 2014. The characteristics and measured values of the pump stations are presented in Table 1. The required data were measured and recorded in-situ in all pump stations. The discharge of pump stations, the current intensity and voltage in electrical panels as well as the technical specifications of pumps and electrical motors were recorded. To measure water pressure head at the outlet of wells and pump stations, the pressure gauge of pump stations was applied, and if there was no pressure gauge installed at the station, it was set up. The discharge was measured using the volumetric method. As in the studied pump stations, the pump and the motor were connected directly or by using a coupling so that the efficiency of power transmission could be considered 100% (Rezvani et al., 2010).

Components of the overall efficiency of the pump station

The total efficiency of a pump station is the product of electrical, hydraulic, and mechanical

Table 1
Characteristics of Studied Pump Stations

Pump station	Location	Pump type	Power	Discharge	Monomeric discharge head	Outlet head of pipeline
			kW	$l\ s^{-1}$	m	m
1	Qazvin	Submersible	37	67	22	22
2	Qazvin	High pressure	30	28	23.5	24
3	Qazvin	Submersible	37	30	30	30
4	Qazvin	Submersible	75	60	46.5	44.5
5	Kermanshah	Submersible	55	7	145	138
6	Kermanshah	Submersible	37	5.7	152	144
7	Kermanshah	Submersible	30	7.9	76	73
8	Kermanshah	Submersible	30	4.5	110	108

efficiency. Electrical efficiency values are based on the results of modeling with PSAT software (PSAT, 2000). The hydraulic efficiency of a pump is defined as the ratio of hydraulic power output of the pump and mechanical power input to the electromotor.

Hydraulic power input to the pump is given by:

$$Ph = \gamma QH \qquad (1)$$

where Ph: hydraulic power (watts); γ: specific gravity of water (9.81 $kN\ m^{-3}$); Q: the flow rate of pump output ($l\ S^{-1}$); and H: static head at the pump outlet (m). The mechanical efficiency of the pump station is the ratio of the head of water at the outlet of the pump station to the generated head at the outlet of the pump (Richards & Smith, 2003).

Pump systems assessment tool (PSAT)

Pumping system evaluation software has been developed by the US Office of Energy Efficiency and Renewable Energy. This software uses information on pumps, electromotors, and field data collected during the operation to calculate parameters and components to analyze pump stations. The model input data are based on the field visits and other documents obtained during the operation of pump stations. The local price of 1 kWh (tariff for agricultural consumption) was US$0.004 based on the 2015 pricing. Accessible efficiency reported by the pump manufacturers was gathered from their catalogs. The maximum allowable electricity from PSAT software is fed into the software input window. Table 2 contains information about studied pump stations for PSAT software.

The software output is provided to the user for both pump station designing and operation. In this study, operation was considered. The software provides two columns for every pump sta-

Table 2
Input Data for PSAT Software

Pump stations	Location	Accessible efficiency	Maximum allowable electricity	Consumed electricity	Voltage
		%	amps	amps	v
1	Qazvin	78	70.2	65	372
2	Qazvin	72	57.5	51	375
3	Qazvin	78.5	70.2	63	378
4	Qazvin	77	141.8	132	372
5	Kermanshah	85	102.6	98	353
6	Kermanshah	85	70.2	63.7	363
7	Kermanshah	80	57.5	46.7	390
8	Kermanshah	82	57.5	51.5	375

Table 3
Quantities of Carbon Dioxide Emissions from Various Sources (Weisser, 2007)

Plant type	Minimum $gCO_2eq\ KWh^{-1}$	Maximum $gCO_2eq\ KWh^{-1}$
Gas power plant	440	780
Hydroelectric power plant	1	34

Table 4
Electromotor, Hydraulic, Mechanical Efficiency, and the Total Efficiency of Pump Stations (%)

Pump stations	Location	Electromotor efficiency	Hydraulic efficiency	Mechanical efficiency	Total efficiency of pump
1	Qazvin	90	43.1	91.7	35.5
2	Qazvin	89.6	24.7	92.3	20.4
3	Qazvin	90.1	26.8	93.8	22.6
4	Qazvin	92.9	40.1	92.7	34.5
5	Kermanshah	90.9	21.6	93.2	18.3
6	Kermanshah	90.1	28.5	92.3	23.7
7	Kermanshah	89.8	26.6	91.3	21.8
8	Kermanshah	89.6	20.0	95.6	17.1

tion: the actual situation and the optimum situation. Software output parameters include pump efficiency, nominal power of electromotor, power of electromotor shaft, power of pump shaft, electromotor efficiency, power factor of electromotor, current of electromotor, annual cost of energy, and the potential for savings of energy.

The environmental impact of electricity production

Greenhouse gases, including carbon dioxide, can hold heat for a long time, causing global warming. Table 3 shows the amount of carbon dioxide emissions when generating electricity for gas power plant and hydropower plant (Weisser, 2007).

RESULTS AND DISCUSSION

Based on field interpretations, electromotor efficiency, hydraulic efficiency, mechanical efficiency, and the total efficiency of pump stations are presented in Table 4. Results showed that the total efficiency of studied pump stations is between 17.1 and 35.5%, being 24% on average, which is in agreement with Yates and Maurice (2006). Therefore, it is necessary to optimize energy efficiency, so the current conditions should be considered. The evaluation of the pump station efficiency in different sectors (motor, pump, and pipe network) showed that the biggest drop in efficiency happens in the power conversion of electromotor shafts to the hydraulic power of pump in the output point. The reasons for low efficiency in studied pump stations are consistent with those presented by the US Department of Energy (PSAT, 2000). According to the survey carried out in this research, almost all electro-pumps are used in outside of the scope of the best efficiency point (BEP). This mainly happens because of mistakes made when choosing a pump. The efficiency of the studied stations, except for the station No. 7, is not appropriate for the reasons such as incorrect estimation of flow rate and pressure of the network by the designer and lack of proper irrigation programs for operator. Another reason for the pump malfunction is the excessive safety factors applied by designers. This causes an error in the proper pump selection. At pump stations No. 3 and 4, as the pump size was overestimated, farmers used the equipment,

Table 5
PSAT Estimations of Annual Savings Potential of Energy Expenditure

Pump stations	Location	Situation	Annual energy consumption (MW h)	Annual energy cost (US$1000)	Annual potential saving (US$1000)
1	Qazvin	Current situation	326.5	1.3	0.7
		Optimized	157.3	0.6	
2	Qazvin	situation	256.1	1	0.7
		Current situation	79.4	0.3	
3	Qazvin	Optimized situation	320.2	1.3	0.9
		Current situation	99.1	0.4	
4	Qazvin	Optimized situation	643.8	2.6	1.3
		Current situation	313.9	1.3	
5	Kermanshah	Optimized situation	444.5	1.8	1.4
		Current situation	11.6	0.4	
6	Kermanshah	Optimized situation	289.6	1.2	0.8
		Current situation	94.3	0.4	
	Kermanshah	Optimized situation	216	0.9	0.6
7		Current situation	64.5	0.3	
8	Kermanshah	Optimized situation	237.5	0.9	0.7
		Current situation	56.8	0.2	
		Optimized situation			

such as bypass system, for pressure adjustment, resulting in a waste of energy. In pump station No. 4, the coupling of pump and motor was out of balance. This causes the bending moments at the pump and motor coupling and vibration; furthermore, it increases the depreciation of the electro-pump and decreases the hydraulic efficiency in the output point (Rezvani et al., 2010). Optimizing energy consumption in pump stations will contribute to the reduction of energy consumption, the saving of the operating and the maintenance costs, environmental pollution mitigation, and energy resources conservation.

Annual energy consumption based on PSAT software output

The PSAT model estimations of the annual saving potential of energy are presented in Table 5. According to Table 5, with optimizing the existing pump stations and pumps, operation costs could be reduced from US$600 up to US$1,400 annually, which is remarkable. For a lifetime of 20 years, a total saving of US$12000-28000 can be achieved.

Estimation of the potential for productivity improvement according to PSAT software

Table 6 presents the estimated potential to increase productivity by optimizing energy con-

Table 6
Estimating the Potential to Increase Productivity by Optimizing Energy Consumption in Real Conditions

Pump stations	Location	Productivity level (%)
1	Qazvin	48.2
2	Qazvin	31
3	Qazvin	31
4	Qazvin	48.8
5	Kermanshah	25.1
6	Kermanshah	32.6
7	Kermanshah	29.8
8	Kermanshah	23.9

Table 7
Carbon Dioxide Reduction Potential by Optimizing Pump Stations

Pump stations	Location	Energy saving when optimizing	Gas plant		Hydropower plant	
		MWh	Min (Mg)	Max (Mg)	Min (Mg)	Max (Mg)
1	Qazvin	169.2	74.4	132	0.2	5.8
2	Qazvin	176.7	77.7	138.8	0.2	6
3	Qazvin	221.1	97.3	172.5	0.2	7.5
4	Qazvin	329.9	145.2	257.3	0.3	11.2
5	Kermanshah	432.9	190.5	337.7	0.4	14.7
6	Kermanshah	195.3	85.9	152.3	0.2	5.2
7	Kermanshah	151.5	66.7	118.2	0.2	6.1
8	Kermanshah	180.7	79.5	140.9	0.2	6.1
Total		1857.3	817.2	1448.7	1.9	63.1
Average		232.2	102.2	181.1	0.2	7.9

sumption in real conditions. According to Table 6, the productivity can be improved by 23.9-48.8%. This confirms the report results of the US Department of Energy (PSAT, 2000). As the above values are low, even with the maximum value, i.e., being 48.8% in the best case, it is obvious that a big amount of energy is wasted. A fundamental reform is necessary for pump stations. According to the US Department of Energy (PSAT, 2000) and the PSAT output, the main reasons for the low energy efficiency in pump stations are improper operation and poor quality design of pump stations. Also, these results support the importance of evaluation and optimization of pump stations.

Analysis of the environmental impact of energy efficiency

Table 7 reports the potential to curb CO_2 emission by optimizing pump stations. As can be seen, by optimizing energy consumption in the studied pump stations, a huge amount of about 1857 MWh electricity can be saved. The potential for reducing CO_2 emission as the main greenhouse gas is 817-1449 t. In other words, on average, 102-181 t of CO_2 mitigation can be achieved. The results of Weisser (2007) also support these findings.

CONCLUSION

In a proper pump station design, several issues should be considered such as proper pump and electromotor selection according to system requirements, the application of highly efficient electromotor, the application of two or more pumps instead of only one single pump with a high capacity, the use of appropriate size of pipes, fittings, and valves, the avoidance of the use of such equipment as bypass, the application of pumps with respect to the best efficiency point, the non-use of pump stations in the peak hours of electricity consumption in the country, periodically balancing the electromotor and pump by farmers to prevent vibration, depreciation, and loss of power consumption, the use of inverter as well as equipment such as soft starter, having an on-time maintenance program.

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