Evaluation of methods for reducing the total cost in rural water pumping stations in Iran: a case study
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ABSTRACT
With regard to increasing energy costs, the issue of reducing energy consumption can be vital and essential. Pumping systems are one of the most widely used energy consuming systems in the water supply network. This work studies the optimization of Goharbaran pump station in Sari (Iran) with the purpose of achieving some extendable effective strategies which can be applied to the other ABFAR pump stations. After the field study, identifying the existing systems, and considering different methods of optimization, three methods have been analyzed and discussed in detail, i.e. using variable speed drives, selection of an appropriate pump arrangement, and load transfer from peak hours. The results show that determination of the exact operating point of the characteristic pump curves and considering the specific energy consumption index in the pump selection can significantly decrease the energy consumption. Also, it is found that utilizing appropriate planning for telemetry can lead to an adequate reduction in the consumption costs. Pilot pump station (the pump station chosen for investigation) results indicate that combining the two approaches of load transmission and selection of an appropriate pump can lead to a decrease in the operation cost of up to 36%, and also a considerable reduction (17.8%) in the energy consumption.

Key words | energy cost, optimization, pumping station, selecting the appropriate pump, variable frequency drives, water supply system

NOMENCLATURE
AS Annual net cost saving achieved, €.year⁻¹
BEP Best efficiency of pump, %
C Cost, €
CC Capital cost, €
CP Consumption patterns, m³.h⁻¹
H Height level, m
Hₜot Total head, m
P Power, kW
PB Payback period, year
Q Nominal pump discharge, m³.s⁻¹
SEC Special energy consumption index, kWh.m⁻³
T Time, h
η Pump efficiency, %

η' Electro-motor efficiency, %
γ Fluid special weight, kg.m⁻².s⁻²

INTRODUCTION
Increasing productivity in installations and equipment for the water industry is one of the basic demands of large-scale management, and from the viewpoint of all experts addressing this issue is very important. Man has found that he can largely increase working efficiency by optimizing energy consumption and revising system performance. Besides, research also seeks to raise the level of productivity. The high cost of energy has led
to new approaches in order to reduce the cost, and this has been achieved largely by optimizing energy consumption and performance management. Discussion of energy is important from both economic and environmental perspectives. Optimizing energy consumption means that lower power consumption can be achieved by adding new equipment or changing it under better management. Optimization efforts require a budget which returns investment in the long-term due to reductions in energy consumption and cost savings.

Many studies have been conducted into the efficiency of pumping systems in developed countries, such as the United States, which show the potential of these systems in reducing energy consumption and consequently decreasing the costs of operating the systems. The United States Department of Energy (US DOE) published a report entitled US Industrial Motor Systems Market Opportunities Assessment in 1998, which statistically analyzed the efficiency of different systems in the USA with electric motors, and accordingly the performance improvement in the fluid systems of pumps, compressors and fans led to a 62% reduction in energy consumption of these electric motor systems. This reduction does not consider the potential of increasing the efficiency of the engine itself (DOE 2002). Another study at the Technical Research Center of Finland in 1996 considered 1,690 pumps in 20 different plants. The results indicate that the average efficiencies of the studied pumping systems are less than 40%, and in 10% of the cases, the working efficiency is lower than 10% (Galitsky 2008). Based on other studies in different countries, pump power consumption has been estimated on average to account for from 20 to 22% of all electricity generated in the world (DOE 2002; European Association of Pump Manufacturers 2004). So based on the high rate of energy consumption of this equipment, evaluating their efficiency and power consumption is a critical part of the world studies in order to achieve optimization and reduction in energy consumption.

There are several optimization techniques that can reduce the energy consumption of a pump, which are discussed later in this article. Most of the research that has been done so far on this issue discusses determining the effectiveness of a solution for one part of a system by auditing it. The important point here is attention to the word ‘system’, because efficiency of a pump should not be confused and assumed to be equal to the efficiency of a ‘pumping system’. These two parameters are not independent of each other, but can be quite different to each other. When the efficiency of a system is discussed, the boundaries for calculating the efficiency go beyond the pump and include all components in the system. In the optimization process and calculation of the pump efficiency with a systematic vision, not only are individual components of the system considered but also the whole system, with its expected input and output, should be studied in detail. In other words, focus on the study of a system component (e.g. a pump) is transferred to the whole system. Abadia et al. accordingly, by defining the method for calculating the global energy efficiency including the pumping energy efficiency, which depends on the efficiency of the pumping stations, and the supply energy efficiency, which depends on the spatial distribution and layout of the system, caused an energy saving of 34.3% with respect to current energy consumption (Abadia et al. 2008, 2012). Also previous studies in developed countries and current experience in Iran show that most design engineers do not consider the lifetime cost of the system during the system design (Ketema & Langergraber 2015). In pumping systems, the percentage of various expenses over their lifetime, on the one hand, depends on the nature of the system and, on the other hand, relates to the pump function during the lifetime of the system. Figure 1 shows an example of the lifetime costs for a pumping system (Galitsky 2008). According to an estimated law, if the amount of pump function time is more than 2,000 hours (such as in pilot pump stations), the cost of energy consumption will be the dominant cost of the lifetime (Frenning 2001).

Figure 1 | An example of the lifetime costs of a pumping system (Galitsky 2008).
Also, the other important factors contributing to low efficiency of a system are related to inappropriate methods for control of the flow, system changes over a time interval, using a pump with low efficiency, and inadequate maintenance systems (Ketema & Langergraber 2015). One advantage in reducing the path of energy consumption in a pumping system is its short payback period (PB) which can be immediate or after a few weeks in some systems, with the average being about 1.5 years, and then results in reduction of the total costs (DOE 2002). Another notable point is that energy consumption optimization in a pumping system finally results in a state in which the pump works closer to its own best efficiency of pump (BEP), leading to improved pump operation, reduced vibrations and forces imposed on the shaft, and eventually to a significant reduction in the pump's maintenance cost (Ketema & Langergraber 2015).

In many similar projects, the audit was studied in the pilot pump station by analyzing only one of the methods of optimization. Therefore, this research performed an optimization study on the energy consumption of the Goharbaran pumping station, of Sari city, with the purpose of developing effective strategies for optimizing all stations in Mazandaran province under the Rural Water Company. After identifying the existing systems and calculating the power cost, various strategies are proposed and the effectiveness of each strategy in the optimization of energy consumption in the pumping station is analyzed and discussed. Finally, the results are expressed for a combination of strategies.

METHODS FOR REDUCING ENERGY CONSUMPTION

One of the activities that has previously been used to save energy in electromotive systems is applying an engine speed controller and soft starters. The purpose of these systems is to give the machine the capability to operate at a speed that is closer to the optimum. This technology will significantly change the flow rate and production head of the pump by changing the RPM of the motor so the pump operating point, which is the intersection of the pump and system curves, will be at BEP and hydraulic energy losses will be reduced to zero (Rahimi & Naderi 2010). Nowadays use of this technology has found global scope. In the research that was conducted by Barutçu et al. for irrigation systems, the amount of energy required varied according to the seasonal changes of flow and pressure and the time of operation. So by using a variable speed pump, energy consumption is dramatically reduced (Barutçu et al. 2007). Also, in a case study by Fazeli et al., a 75% decrease in the rate of occurrence of incidents and failures was achieved while using variable multi-speed pumping systems, resulting in an improvement in optimized network usage and cost reductions (Fazeli et al. 2009). Other studies also indicated an increase in the lifetime of the system, reducing water losses and soft starters, and thereby reducing damage to the components of the well by using this system (Fazeli et al. 2009; Mutikanga et al. 2010).

Other methods to achieve optimization are the use of intelligent control systems and telemetry including water level control, flow rate control, pressure control, alarm systems and monitoring. Zhang et al., by using a pump control model, could increase the water demand from 1,720 to 2,200 m³, and eventually caused a reduction in operation cost (Zhang et al. 2012). The main tool to reduce the cost of the pump control procedure is transferring the load from peak hours to low load hours. Since the electrical power consumption by consumers varies at different hours of the day, the electrical power changes curve (Figure 2), which determines the electrical energy consumption over time, is divided into three areas: the low load region, intermediate load region and peak load region (IPD 2013).

In such situations the use of technical and economic methods is very important to maintain a balance in

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**Figure 2** | Daily electrical power consumption of Mazandaran province (Iran) (IPD 2013).
consumption at low load and peak load hours, among which we can mention the pumped storage power plants.

So, we can transfer some additional energy which was produced at low-consumption hours to peak-consumption hours by storage as potential energy. This can be very useful based on the price tariff of the power distribution company (Khaksar 2006; IPD 2013). Pulido-Calvo proposed a model to determine a regulating reservoir’s capacity and establish an annual pumping schedule that accounts for energy costs. The solution was determined using an algorithm to calculate the optimal reservoir dimensions to obtain the optimal annual pumping for a pressurized irrigation delivery system, located in southern Spain, to the reservoir, based on the concept of the ‘emptying period’. The analysis indicated that the total costs can be further reduced by adjusting the demand pattern to match better with low load hours (Pulido-Calvo et al. 2006b; Pulido-Calvo et al. 2007).

Selecting an appropriate pump, and using several pumps, is one of the most important strategies for reducing energy consumption in pumping stations. In order to increase the efficiency of systems with variable required capacity, a combination of pumps may be used, and based on the system’s required capacity more or fewer pumps will be put into service. In order to calculate the exact discharge produced by the system, the equivalent parallel pumps curve and the system curve should be determined and their crossing point identified, because the final produced discharge of parallel pumps isn’t equal to the sum of every individual pump’s discharge but is always less than this amount. This is due to the increase in flow speed and thus pressure drop as a result of increasing the discharge in to the pipe network (Lakzaeyyanpur 2006; REC.Co 2011). By using this method, Pulido-Calvo et al. compared 34 models of pump combinations; the selected one had the lowest annual operation cost, caused by a 70% reduction in energy consumption (Pulido-Calvo et al. 2006b). Note also that, unlike the Pulido-Calvo work (Pulido-Calvo et al. 2006b) where the same pumps were used, a combination of various pumps will be discussed in this paper.

Also, using solar energy for supplying and transferring water has been focused on recently. But due to the high expense of photovoltaic plates and the inexpensiveness of the power cost for pumping water in Iran, this plan’s PB would extend beyond 20 years, suggesting a lack of economy given its defined 20-year life cycle. Furthermore, electrical energy produced by diesel and gas generators for use at peak-load times was evaluated, and results suggested that although the gas cost in Iran is inexpensive, this idea has a long PB too (Heydari & Surei 2010).

Other optimizing strategies, such as using a capacitor bank for removing the reactive load (Vakili tahami 2010), using stabilizers for stabilizing the grid voltage (UPS-Co 2014) and technical consideration of suction tubes (Farakoh.Co 2013) can be considered. Moreover, these methods have already been considered in the pilot pump station or otherwise other similar functional methods have been used. Further, some managerial methods, such as controlling leakage in the water supply or selecting an optimal diameter, require examination of the hydraulic system, which is outside the bounds of the station and beyond the scope of this research (Sarkardeh & Khodashenas 2008).

So, regarding the mentioned issues, three strategies of (1) using an engine speed controller, (2) a telemetry program for transferring the load from peak hours to low hours, and (3) selecting an appropriate and optimal pump are audited in the Goharbaran station of Sari city.

INTRODUCING THE STUDIED STATION

Goharbaran stations (1) and (2) are located in the northern Iranian province of Mazandaran and Sari city (Figure 3). Sari has a hot-summer Mediterranean climate. Winters are cool and rainy, whilst summers are hot and humid. Sari’s 2005–2006 statistical weather information shows that the average annual precipitation is about 790 mm, it has an average annual temperature of about 15 °C, the average relative humidity is about 70% and altitude is 132 metres. A nearly 6 cm annual loss in groundwater level has been observed.

According to Figure 4, which shows a profile of the water pumping systems in Goharbaran stations (1) and (2), the supply source for the water in Goharbaran station (1) is a well located near Alookandeh, a village in the suburbs of Neka city. The stored water in the ground tank at Goharbaran station (1) (the entrance from the well) is pumped by two floating electro-pumps, version 345/2 with nominal power of 15 kW, into two paths of the ground tank of Goharbaran station (2) and the aerial tank of Goharbaran station (1). Similarly, this version of the electro-pump has been used for pumping water from the
ground tank of Goharbaran station (2) into its aerial tank. Also, the characteristics of the mentioned elements and their conditions are as follows (ABFAR 2011):

- The volume of the ground tank of Goharbaran station (1) is 1,000 m$^3$ and the volume of the ground tank of Goharbaran station (2) is 500 m$^3$. Both stations’ aerial tanks have a base at a height of 24 m and a 150 m$^3$ volume.

- Based on reported consumption data from Mazandaran’s ABFAR in 2011, these stations serve 3,752 households, with an average consumption of 16.4 m$^3$ of water entering into supply per month. So, the daily consumption in Goharbaran stations (1) and (2) is 950 m$^3$ and 1,150 m$^3$, respectively.

- According to examination of the electricity bills in the first 8 months of 2012, after subsidies were stopped in November 2010 and changes made to tariff prices, the annual cost in Goharbaran station (1) is about 85,320,000 Rials (GBP 1957.8).

- The price of one variable frequency drive (VFD) equipment set is considered to be 55,250,000 Rials (GBP 1268).

- The pipeline between these two stations is made of asbestos-cement, with a 7,700 m length and a 250 mm diameter.

- All tanks have a 3 m height.

In the available system (Figure 4), there are three places for using VFDs: 1, in pumping from the ground tank of Goharbaran station (1) to the ground tank of Goharbaran station (2), 2, in pumping from the ground tank to the aerial tank of Goharbaran station (1), and 3, in pumping directly from the ground tanks to the networks.
Regarding the completed calculation and maintaining constant head loss and thus constant pressure in modes 1 and 2, we can save on energy consumption by selecting appropriate pumps. In mode 3, although the effect of VFD on pressure control and the required discharge is significant, due to demand increasing the use of a bigger pump is needed at certain times to supply the water from tank storage. So, in this research, for modes 1 and 2, pumping into both stations’ aerial tanks and the ground tank of Goharbaran station (2), the use of both the available pumps and a selected appropriate pump was considered.

Regarding the examinations conducted, we can conclude that the reason for selecting the pump in pilot pump stations is based on the need for consumption and supplying the required water using a powerful pump with high discharge. Here, decreasing the size of the electro-pump and using several small pumps instead of one big pump can help increase the pumping efficiency and life cycle and also reduce energy consumption by increasing the power factor.

In addition, the following assumptions were considered in the analysis:

- Since the stations represent the system in this study, only input and output are considered; leakage losses in pumping are neglected.
- Based on experience, the connection-based local drop in water transferring from a ground tank to an aerial tank is considered to be about 2 m in a station.
- Efficiency of electro-motors, in accordance with some studies and catalogs, is assumed to be 95% (ABFAR 2011; Abadia et al. 2012).
- Regarding the use of capacitors in the Goharbaran stations’ electrical installations, losses resulting from electro-motor inductive power are neglected.
- Sari is just a plains region and, according to reports, static loss resulting from the height difference of the two paths is negligible.
- The suction tube’s conditions are assumed to be standard.
- Regarding the use of flow-meters in aerial tanks, the minimum water height can vary.
- The value of the euro at the time of this study, November 2010, was 18,390 Rials (Mirzakhani 2012).

## STATUS QUO ANALYSIS AND EXPLAINING THE REQUIRED RELATIONS

### Minimum required discharge

Given that in this research our pumping type is tank to tank, with respect to data collected from ABFAR company’s experts and with a normal daily consumption (950 m³) and confidence coefficient of 1.5 for peak consumption hours, the minimum required discharge is about 70 m³/h:

\[
\text{Minimum required discharge } (950 \times 1.5) \, \text{m}^3/24 \, \text{h} = 70 \, \text{m}^3/\text{h}.
\]

### Determining a pump’s operating point

In pumping from the ground tank to the aerial tank, the pump’s discharge is always fixed, along with head losses along the path of Goharbaran station’s ground tank to its aerial tank, so the installed pump’s operating point is determined by trial and error. The height difference between the suction tube and the aerial tank was reported by ABFAR to be 25 m and, with adding the transfer pipe’s friction loss (calculated by the software of a pipe pressure loss calculator) and the connections’ local drop, the average estimated head related to flow discharge varies from 27 to 29 m. Based on the pump catalog (the bolded point in Figure 5), the pump’s discharge at its maximum value is equal to 100 m³/h, its efficiency at this value is 66% and its operating point is at 140% of the BEP’s discharge. According to Figure 5, more produced head and discharge is required (Pumpiran.Co 2012).

### Calculating the consumption power

If the pump’s efficiency is \( \eta \) and the electro-motor’s efficiency is \( \eta_0 \), then the required power for running the pump is calculated by Raeisi (2011):

\[
P = \frac{\gamma \times Q \times H_{\text{Tot}}}{\eta \times \eta_0}
\]
So, energy consumption in the status quo is 12.6 kW.

\[ P = \frac{9.81 \times \frac{N}{m^3} \times \frac{100}{3,600} \times 29 m}{0.66 \times 0.95} = 12.6 \text{ kW} \]

Similarly, since the pipeline between the two stations, which is made of asbestos-cement, has a 7,700 m length and 2,000 mm diameter, for water pumping between the two stations' ground tanks, the head loss is calculated to be 13.2 m and the consumption of power – with the same efficiency and discharge – is 5.7 kW according to the above-mentioned software.

**Special energy consumption index**

According to Equation (1), consumption power certainly reduces with reducing discharge. So, one parameter which is important in pumping tank to tank – indeed, in pumping a given volume of water – is the special energy consumption index. The special energy consumption index is the consumption energy for providing one unit of product. For pumping systems, this index can be written as the ratio of consumption of electrical energy to the pumps’ discharge:

\[ \text{SEC} = \frac{\text{consumption energy kWh}}{\text{discharge } m^3} \] (2)

The smaller this index is, the more efficient the system is. This can be explained as: energy consumption is lower for a given discharge, so it will result in a saving in energy and costs.

Here, \( \text{SEC} \) – the special energy consumption index – is calculated as follows:

\[ \text{SEC} = \frac{12.6 \text{ (kW)}}{100 \text{ (m}^3\text{ h)}} = 0.126 \left(\frac{\text{kWh}}{\text{m}^3}\right) \]

Similarly, for water pumping between each station’s ground tank and aerial tank, this index is calculated to be 0.057.

**PB**

In energy optimization studies, for determining an appropriate strategy, special attention is paid to reducing energy consumption and costs as well as PB. PB is defined as capital cost (CC) divided by annual net cost saving (AS) (Beggs 2010):

\[ \text{PB} = \frac{\text{CC}}{\text{AS}} \] (3)

**Determining the consumption pattern**

Regarding significant change in water consumption in small networks (villages), we determined the daily discharge changes for stations based on reference patterns (Figure 6).

**Electricity costs for Goharbaran stations (1) & (2)**

Electricity costs calculated by the Tavanir organization have different tariffs for different consumers. Consumption hours are divided into three parts: low load (11PM–7AM), intermediate load (7AM–7PM) and peak load (7PM–11PM). For water pumping stations with a power of 30 kW and more, these costs are calculated as shown in Table 1, by the consumption tariff of the agriculture sector’s water production and tariff code 5-b (EECM (Energy Consumption Management – in Iran) 2011).

Assuming equality of pumping and consumption, according to the consumption graph in Figure 5, the daily energy consumption cost for water pumping from Goharbaran...
be found that by November 2012, 19.4% of costs were related to the contract’s demand (CCRSWEB 2015).

**OPTIMIZING STRATEGY**

Among the mentioned strategies, three are very important in the pilot pump station, and here we evaluate their effects.

**Using an engine speed controller**

Pumping system design should meet the maximum required flow as well as use appropriate methods for flow control based on the system’s nature and its characteristics, such that at the time of needing low flow, minimum energy losses result. In many systems, flow control valves and by-pass lines are used, which have the most energy losses, while variable speed engines and parallel pumps, which help reduce energy consumption, are used less often. Figure 7 shows the comparison of energy consumption for different methods of flow control (Prachyl 2010; Raeisi 2011).

Mostly, pumping systems are designed to meet the highest demand. However, a pump’s function in design settings can be met at only limited times, and so a pump mostly operates with low efficiency and away from the BEP point and, in addition to reducing the electro-pump’s life, this also results in increased energy consumption. In such conditions,
using engine speed frequency controllers (VFD) with changing engine speed and control of the network pressure, set the pump in the best operating conditions. Using such equipment is effective if the pump’s discharge operating point is greater than the BEP’s discharge. Here, VFD results in reducing energy consumption by reducing frequency and thus, reducing engine speed with a constant discharge at the BEP point. For example, with a 20% reduction in discharge, energy consumption reduces by 49% (Raeisi 2011).

A pump’s flow rate and production head and thus its operation curve change rapidly. Hydraulic energy losses will be reduced to zero if the pump’s curve intersects the system’s curve at the discharge point (a pump’s operating point is the intersection of the pump’s curve and the system’s curve). In this method, we can use different equipment, such as engine speed controllers, variable speed engines, variable speed drives, etc. (Rahimi & Naderi 2010).

Reducing costs by load transferring from peak hours to low load hours

In this study, the characteristics of numerous ground and aerial tanks in our given stations’ water supply networks and their storage potential were considered. According to this approach, given the network’s demand and tank volumes, we tried to reduce ABFAR’s power consumption costs by storing water in low or intermediate load hours and programming its use in peak load hours. Furthermore, ABFAR, as an organization which consumes 20% of the total electrical energy of the country, has a strong potential for reducing energy consumption which would lead to improving the balance in the plant’s production status and load curve (Ketema & Langergrabner 2013).

Generally, reducing consumption costs with this method includes using water pumping in low and intermediate load hours and storing it as potential energy in the two stations’ aerial tanks and in Goharbaran station (1)’s ground tank, and using it during appropriate hours. Hence, the power cost transfers to low hours instead of peak hours. This strategy has two main conditions:

(a) At initial low load hours or at the end of peak hours, the height of the water in the tank should be at its minimum allowed level.

(b) At the end of the low or intermediate load hours (based on the tank volume and consumption pattern (CP)), the height of the water in the tank should be at its maximum allowed level.

So, here, the pump is turned on or off if the water level reaches its maximum or minimum allowed level, 30 cm from the ceiling and 15 cm from the floor, respectively, by using telemetry equipment and monitoring and control systems.

Now, based on the above terms and Figure 8, we should determine the minimum and maximum optimal height within the time series in order to access the minimum cost without any change in energy consumption. That is, cost (C) optimizing, by time limit (T), CP and height level (H) of the water in the tank is as follows:

\[ \text{Min } C = f(H, T, CP) \]  

(4)

The storable volume (the volume of the ground or aerial tank) and its ratio to the total consumption in 1 day is a very important factor. Since the water is transferred to the consumer by the aerial tank, some new terms should be determined based on this tank. We have the following terms for a 1-hour period:

- Water storage in some 1-hour periods in which consumption is more than the pump’s discharge.
- A condition for preventing the pump’s sequence for turning on and off.
- Observing the CP and controlling the maximum allowed height at the end of the intermediate load hours in order to access the first main condition.

![Figure 8](https://iwaponline.com/aqua/article-pdf/65/3/277/398774/jws0650277.pdf)
Selecting an appropriate pump

In pumping stations, the engine and load have special unique characteristics, so the engine’s operating characteristics should be appropriate for the mechanical load characteristic. Selecting an engine with excess power for loading leads to increasing the initial cost of the engine as well as other costs, such as cabling, installing, running and repairing. On the other hand, if the selected engine is bigger than the need, it doesn’t work at the full load or near full load. Thus, its efficiency becomes less than its maximum level, and this leads to important and serious problems in optimizing energy consumption. As we mentioned before, in tank to tank pumping, selecting an appropriate pump and using equipment such as VFDs are effective measures, as they provide a constant pressure drop and enable selection of a pump that works effectively. In the field of optimization using pump multi-purpose planning, Larralde and Ocampo have conducted many studies. According to their work, we should consider the pump operating point and its proximity to the BEP point (Larralde & Ocampo 2010a, 2010b). In their research, examining the optimal conditions for maintaining electro-pumps, Taheri asl et al. point to the necessity of approximating the pump’s operating point to the BEP, and introduce the special energy consumption (SEC) index as a criterion for determining the system’s optimality in terms of energy consumption in every station (Taheri asl et al. 2009; Taheri asl & Sayadzadeh 2009). After determining on demand discharge of the plan and estimating the total head loss, the engineers use the pumps’ overlapping curves, compare those pumps within the given head and discharge limits in terms of efficiency, and select the pump with the most efficiency in order to select a floating pump for the water company. In this case, the exact operating point and thus consumption estimation are not always determined, and a pump with a low efficiency is sometimes selected. On the other hand, selection of a pump by engineers becomes more difficult when we consider using some smaller parallel pumps for securing the on demand discharge. This is due to mismatching of the small parallel pumps with the head loss defined in the pumps’ overlapping curves, and to the complexity of the calculation.

In this project, for selection of an appropriate pump, firstly we draw the path of the head loss curve for different discharges and then draw the pump characteristics curve as a single pump or several parallel pumps. Using this graph, we determine the exact operating point of the pump and also solve the complexities related to using some smaller pumps.

Finally, comparing discharge index to consumed power, we compare the used pumps and select the most optimal pump in terms of energy consumption.

Note the following points for selecting a pump:

- Using the pump in very low discharges (10% of the BEP’s discharge) leads to an increase in the pump’s temperature.
- Using the pump in low discharges (up to 40% of the BEP’s discharge) leads to wear of the bearings and mechanical seals.
- Using the pump in very high discharges (120% BEP’s discharge) leads to increased cavitation.
- Using the pump at points away from the BEP leads to increased flow disturbance and intensifies friction.

RESULTS AND DISCUSSION

Using an engine speed controller

Using VFD equipment changes the pump characteristics by reducing the engine speed such that in the new conditions, the pump is located at a head of 28 m and at the BEP point (Figure 9); that is, it will work with 76% efficiency and a discharge of 72 (m³/h) (Pumpiran.Co 2012).

Here, the consumption power and SEC index are as follows:

\[
P = \frac{9.81 \times \frac{N}{m^3} \times \frac{72}{3,600} \times \frac{m^3}{s} \times \frac{28}{m}}{0.76 \times 0.95} = 7.61kW
\]

\[
SEC = \frac{7.61 kW}{72 m^3} = 0.1057 \frac{kWh}{m^3}
\]

So, based on the change in the SEC index induced by the VFD, the energy consumption reduces by 16.11%.

Saving percentage = \( \frac{0.126 - 0.1057}{0.126} \times 100 = 16.11\% \)
In this project, regarding synchronous changes in consumption tariff cost and demand cost, the saving rate in the annual cost will be 16.11%, according to the following calculations:

\[ AS = \frac{85,320,000 \times 0.1611}{13,745,050} = 13,745,050 \text{ Rials} \]

and \( CC = 55,250,000 \text{ Rials} \).

\[ PB = \frac{CC}{AS} = \frac{55,250,000}{13,745,050} = 4.01 \]

So, the PB of the plan will be 4 years.

Reducing cost by transferring load from peak hours to low load hours

Pumping from Goharbaran station (1)’s ground tank to its aerial tank

In this plan, we recorded the water consumption rate in Goharbaran network (1) over some 1-hour periods and, based on the pattern and given the tank height of 3 m, we determined the minimum and maximum optimal height according to the defined terms and the audited cost. In the following, after calculating the necessary input water volume, we obtained the required time for the pump to be turned on in each period and the consumption energy (based on the consumption power calculated before) and so the energy cost. The results of water pumping from the ground tank to the aerial tank of Goharbaran station (1) are presented in Table 3.

Now, we present the reasons for selecting each minimum and maximum optimal height in different periods in order to access a superior pattern:

1. 11PM–1AM: Although this 2-hour period is outside of peak load hours and the power cost is calculated as low load hours, experimentally this period sometimes includes high consumption hours. Here, based on engineering experience and in order to develop a confidence
coefﬁcient for creating a balance in loads of power plants, we turn on the pumps equal to the estimated consumption rate and the water is stored in the tank. Also, we select a minimum height of 0.15 m based on the standard minimum height of 0.15 m.

2. 1AM–7AM: Here, in accordance with the condition mentioned previously, regarding reaching the allowed maximum height (2.7 m) at the end of the low load hours, and considering the water consumption rate and calculations of height change by trial and error methods, the minimum optimal height (1.85 m for this aerial tank) with the least cost is obtained.

3. 7AM–11AM: Selecting the minimum and maximum doesn’t have any limitation in this period; but with regard to the condition for preventing the pump’s turning on and off sequence, we should select optimal heights, which are selected in this period at values of 0.3 and 2.7 m.

4. 11AM–2PM: Here, water is stored in the tank to secure the consumption rate over the following hours. So, we select 1.5 m as the minimum by the conducted calculations, and have no limitation for the maximum water height.

5. 2PM–7PM: Considering that the water consumption rate in the power consumption peak hours is more than the storable volume in the aerial tank, we should reach the allowed maximum height (2.7 m) at the end of the intermediate load hours as previously mentioned. Also regarding the water consumption rate and calculations of

<table>
<thead>
<tr>
<th>Time (h)</th>
<th>Consumption (m³)</th>
<th>Input discharge (m³)</th>
<th>Initial height (m)</th>
<th>End height (m)</th>
<th>Maximum optimal height (m)</th>
<th>Minimum optimal height (m)</th>
<th>Maximum consumption energy (kW)</th>
<th>Energy cost (Rials)</th>
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<td>0.51</td>
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<td>2.7</td>
<td>1.85</td>
<td>12.6</td>
<td>976.5</td>
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<td>0.15</td>
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<td>0</td>
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<tr>
<td>Total</td>
<td>950</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>120</td>
<td>15,790</td>
</tr>
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</table>
height changes by trial and error methods, the minimum optimal height (1.7 m for this aerial tank) is obtained.

6. 7PM–11PM: In this period, each kilowatt of electrical power consumed has the highest cost and the period is considered as peak hours. So, we should try to make the water level about 15 cm, or at the minimum allowed level, at the end of this period.

**Pumping between two Goharbaran stations’ ground tanks**

Goharbaran station (2)'s ground tank has a 5,002 m³ capacity and its water is secured by pumping from Goharbaran station (1). Based on two views, the use of low load hours for determining the effect of a telemetry strategy and whether telemetry can be applicable for Goharbaran station (2) or not, are evaluated. Here, it is supposed that a telemetry strategy is used for the aerial tank. So, the CP becomes optimal and influenced by the output water volume of Goharbaran station (2) (Figure 10) and certainly it leads to a better result.

According to Table 3, the daily energy cost of pumping from Goharbaran station (1)'s ground tank to its aerial tank reduces from 19,440 Rials to 15,790 Rials; that is, it reduces by 18.8% and similarly, in pumping between the two stations’ ground tanks, as shown in Table 4, the energy cost reduces by 37.3%.

So, according to Figure 11, the daily energy cost for this pumping station reduces by 10,690 Rials. This is without considering the contract’s demand cost; this is done, our cost reduction will be 22.5%. As shown in the figure, the cost is more than the previous state in the initial low load hours; but then the cost becomes reduced by increasing the power price and decreasing the consumption.

**Selecting an appropriate pump**

According to Equation (1), whenever our head is determined, the best selection is one that gives a state such that for the same energy consumption, the most discharge is produced. Here, the smaller the SEC index is, the more efficiency the system has; we can say that for a given discharge, the energy consumption rate is lower, so it leads to a saving in energy and costs. In selecting the pump, we should consider its height efficiency as well as its low SEC index.

In pumping water from Goharbaran station (1)'s ground tank to Goharbaran station (2)'s ground tank, the path’s head loss for different discharges was obtained (using Pipe Pressure Loss Calculation software) and is shown in the
head v. discharge diagram (Figure 12). As seen, along the path, the head loss increases from 1 to 19 m by increasing the discharge from 25 to 120 m$^3$/h. Also, some floating pumps, model KSB, were experimentally selected and their characteristic curves are shown with single, two or three parallel structures.

These diagrams show the pump’s operation in coping with different head loss, and the pump’s operating point in the pumping system is where the pump’s curve crosses the path curve.

According to Equation (2), whenever the head is determined, the best pump is one that gives a state such that for each kilowatt of consumption power, the most discharge is produced. Based on the diagram, using the options of Table 5 is good. The results show that selecting two parallel floating pumps, model 271/2, leads to a reduction in the SEC index.

The electro-pump type used in Goharbaran station (1) is the 345/2, which has an efficiency of 66% and an operating point at a distance of 140% from the BEP discharge. Now, with an appropriate selection of two parallel floating pumps, model 271/2, the pump’s efficiency increases to 69% and its operating point is located at 110% of the BEP discharge (Figure 13).

Here, the discharge index to consumed power increases from 17.42 (m$^3$/kWh) to 21.19 (m$^3$/kWh). So, based on the change in the SEC index, energy consumption decreases by 17.8%.

\[
\text{Energy consumption percentage} = \frac{0.0574 - 0.0472}{0.0574} \times 100 = 17.8\%
\]

Similarly, based on the diagram in Figure 14 and by selecting two pumps, 293/2, the system curve is crossed by the discharge 100 (m$^3$/h) and the head (29.2 m) at 72% efficiency. Here, energy consumption reduces by 9.7%.

There is an interesting point here suggesting the applicability of the removed electro-pumps in other pumping stations with higher BEP. In this project, selecting an appropriate pump leads to an annual 15,800,000 Rials saving. As a result, considering the cost of buying electro-pumps 345/2 and 271/2-25,080,000 and 16,150,000 Rials, respectively – this plan’s PB is 2 years without using the removed pump, and reduces to 6 months if it is reused.

So, with regard to the wide range of pumping systems in all regions, the plan’s PB will be very short.

**Combination of strategies**

In the previous sections, the influence of each of the optimization methods has been expressed. The combination of

![Figure 12: Path head loss diagram and pump characteristic curves (pumping between the two stations' ground tanks).](image)

**Table 5: Determining discharge v. consumption power of the selected floating pumps, model KSB**

<table>
<thead>
<tr>
<th>Pump mode</th>
<th>Pump number</th>
<th>Nominal power (kW)</th>
<th>Discharge (m$^3$/h)</th>
<th>Head (m)</th>
<th>Efficiency (%)</th>
<th>Consumption power (kW)</th>
<th>SEC (kWh/m$^3$)</th>
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<td>2</td>
<td>3.7</td>
<td>83.3</td>
<td>10.5</td>
<td>69</td>
<td>3.93</td>
<td>0.042</td>
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<td>2</td>
<td>3.7</td>
<td>92.5</td>
<td>13</td>
<td>65</td>
<td>5.74</td>
<td>0.062</td>
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<tr>
<td>271/4</td>
<td>2</td>
<td>5.5</td>
<td>101.7</td>
<td>14</td>
<td>58</td>
<td>7.62</td>
<td>0.0749</td>
</tr>
<tr>
<td>271/2</td>
<td>3</td>
<td>3.7</td>
<td>102.7</td>
<td>12</td>
<td>70</td>
<td>5.9</td>
<td>0.0575</td>
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<td>3.7</td>
<td>109</td>
<td>16.5</td>
<td>69.5</td>
<td>8.65</td>
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<td>100</td>
<td>13.2</td>
<td>66</td>
<td>5.74</td>
<td>0.0574</td>
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</table>
these methods can enhance their performance. Table 6 shows the combination of these strategies. As can be seen, although using VFDs always leads to reduced energy consumption, we can reach the pump’s BEP by selecting an appropriate pump and obtain the same result.

**CONCLUSION**

The increasing cost of energy has led to new approaches in order to reduce the cost, and this has been achieved largely by managing and reducing energy consumption. The water and wastewater industry, due to the widespread use of pumps, is one of the main consumers of electrical energy, and high potential exists for optimization of energy in this sector.

In the past, various studies have been conducted to investigate water pumping stations. In many similar projects, the pilot pump station had been studied by analyzing only one of the methods of optimization. But in this study, research has been conducted in order to optimize the energy consumption of the Goharbaran pump station of Sari city with the purpose of developing effective strategies for optimizing all stations in Mazandaran province under the Rural Water Co. After auditing the systems and the elements of the stations, different types of methods for reducing energy consumption and energy costs were investigated.

For auditing, based on the minimum required discharge and the CP, the operating points of the pumps were determined, then in accordance with reports the electricity costs were calculated. Finally, after evaluating different methods of optimizing in the pilot pump station, it was shown that three strategies, using VFD, telemetry programs and selecting a suitable pump, can significantly reduce energy consumption.

Use of VFD led to a 16% reduction in the SEC index or energy consumption and its cost, with a PB of 4 years.

Selecting an appropriate pump is an important method. Changing the pump, without any CCs, can bring the operation point to the BEP, increasing the efficiency and therefore causing a reduction in the energy cost. In this project, the results showed that this method reduces energy costs by 9.7% with a short PB of 6 months. But the other fact to consider is that, similar to the suggestion of Pulido-Calvo et al. (2006a) who reported a considerable reduction in energy consumption, better choices exist for pump replacement, and now the authors of this paper, in cooperation with the Rural Water Company, are developing software for searching and testing the choice up to a hundred times by a combination of series and parallel pumps. In pumping from Goharbaran station (1)’s ground tank to its aerial tank, by recording the water consumption rate over several 1-hour periods and considering the pattern, and according to the defined terms and the audited costs, we determined the minimum and maximum optimal height of the tank.
With regard to the basis for pumping from Goharbaran station’s ground tank to its aerial tank, the required discharge to its ground tank would be out of the usual CP, and it is necessary for both the ground and aerial tank of this station to achieve maximum or allowed optimum height in the low hours’ load. So, the effect of transferring the load from peak hours to the low load was doubled, that is, the energy cost in pumping from Goharbaran station’s ground tank to its aerial tank reduces by 18.8% (or 3,650 Rials) and similarly, in pumping the two stations’ ground tanks, reduces by 37.3% (or 7,050 Rials). Furthermore, it should be mentioned that this prevents excess energy production in the peak load hours in the plant stations. Also, this plan is more useful for those central pumping stations transferring water to several ground tanks.

It also should be noted that a programming plan and using telemetry has some disadvantages, such as the high cost of telemetry equipment and the need for an expert user. But these projects’ PB’s depend on the ratio of the tank volume to the daily consumption need; the greater this ratio, the greater the cost reduction and the shorter the PB.

It is also suggested that in the case of removing the aerial tanks and using a VFD engine speed controlling system with a big pump for direct pumping to the water supply, this should be used for storing water in the tanks during the low load hours based on the water storage plan in order to transfer the costs of peak load hours to the low load hours, which helps power plants, and the costs are reduced significantly.

### ACKNOWLEDGEMENT

We would like to thank the Rural Water Co. of Mazandaran, for providing the funding for this project.

### REFERENCES


ABFAR 2011 Rural Water Co. (ABFAR) of Mazandaran, monthly reports.


### Table 6 | The results of different optimizing methods

<table>
<thead>
<tr>
<th>Pumping type</th>
<th>Optimizing strategy</th>
<th>Energy consumption reduction (%)</th>
<th>Cost reduction (%)</th>
<th>SEC (kWh/m³)</th>
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</thead>
<tbody>
<tr>
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<td>Present conditions</td>
<td>–</td>
<td>–</td>
<td>0.126</td>
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<td>9.7</td>
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<td>16.11</td>
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<td>23.25</td>
<td>0.11</td>
</tr>
<tr>
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<td>Telemetry + VFD</td>
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<td>25.13</td>
<td>0.1057</td>
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<td>18.5</td>
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<td></td>
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<td>25.13</td>
<td>0.1057</td>
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<td>Pumping between the two stations’ ground tanks</td>
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<td>Telemetry + selecting the pump</td>
<td>17.8</td>
<td>36.01</td>
<td>0.0472</td>
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</table>
Rahimi, A. & Naderi, Z. 2010 Comparison of optimizing energy consumption in the control stations using the automation system and methods of classical setting. The Third National Conference of Irrigation Channels and Drainage, Ahvaz, pp. 7 and 8.
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