Thesis of doctoral (PhD) dissertation

ENERGY USE REDUCTION IN WATER UTILITY SYSTEMS

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Debrecen
2015

1. INTRODUCTION AND OBJECTIVES

Electricity nowadays is the energy resource of choice in every area of life. The level of supply of electricity that serves industrial production and domestic convenience is increasingly harmonized with its environmental effects.

This has become increasingly evident since the focus of interest has turned to renewable energy. In the past, resources seemed endless, and there was a relatively good balance between supply and demand. With growing urbanization and standards of living, and pressure on resources from events like the oil crisis, energy issues have increasingly come to the fore.

The link between energy and the environment has become a daily concern, and this is also true for the water utilities that serve households and industry. There is every sign that energy is the resource that most influences production and services in this increasingly technical age, and it is bound up with environmental protection and the economy.

The second most prominent infrastructural resource is piped water, whose efficient operation is one of the prime indicators of the economic advancement. History has proven several times that it is in the basic interests of society to provide and operate public utilities at a satisfactory standard. In Hungary, developing and expanding water utility networks and operating them efficiently will be one of the greatest challenges for the national economy. A significant influence on its capabilities in this direction will be the consumption and price of energy.

Energy demand, industrial development and population have been growing steadily since the middle of the last century (ENSZ, 1987). It is now widely accepted that our present energy systems, from the primary energy sources to the means of consumption, cannot be sustained. Atmospheric pollution in cities and the global warming caused by greenhouse gases are causes for increasing concern. In addition, the slowly but steadily receding classic fossil fuel sources threaten severe energy shortages.

As these factors develop, one of the key technical, economic and political tasks is to build up a system of energy supply and use which can be sustainably operated on a global scale.

On the energy supply side, the most important task is to employ technology that can reduce the emission of greenhouse gases. This can best be achieved by greater use of renewable energy resources. Political, industrial, economic and technical groups are working together to explore possible solutions and develop new technologies. The goal of energy use is to reduce the rate of consumption relative to GDP. This demands a change in domestic and industrial energy demand and more economic utilization.

Saving energy usually, and fundamentally, involves two options. One is the application of energy-saving technologies and installing more energy-efficient equipment, and the other is to optimize the use of existing systems.

In recent years, the costs of water supply and sewage treatment have been steadily increasing. Service providers are engaged in constant negotiations with the local authorities which own them to have realistic prices accepted.

The present government has imposed centralized state pricing and is trying to gradually reduce these prices. This is because our service is the most expensive in Europe, so that consumers are finding it increasingly difficult to pay service prices that often rise faster than their income. In order to moderate price rises, in line with government endeavours, water utilities regard the constant optimization of energy use in water extraction and supply and sewage treatment as a primary task.

Water supply systems and sewage pumps were originally designed with high capacity. A trend of the last 25 years, however, has been a drastic reduction in water use, leading to a decline in capacity utilization. Identifying and making proper use of surplus capacity can deliver significant savings that can in turn significantly reduce consumer expenses.

Studies of how modifications to the system take effect demand a new, horizontal approach which covers the entire process of water movement from extraction to reservoir. Maximizing energy savings requires an analysis of the energy consumption of supply, treatment and network pumps in operation, so as to determine the optimum pattern of operation.

Pump regulation must achieve optimum energy use, within the constraints, by taking account of the characteristics of every element of the water supply system.

The objectives of the project were:

- to adapt and apply energy use optimization algorithms in measurements of operational energy efficiency (in kWh/m^3) of Hungarian water utilities,
- to use the measurements to determine the potential savings in kWh and long-term operating costs, and in terms of CO_2 emissions,
- to check the attainability, in various water utilities, of the potential savings identified by the studies,
- to evaluate the results as a basis for recommending potential means of energy saving and new means of enhancing efficiency.

The objectives of the project are in harmony with the relevant European Union objectives. *Recital 4 of Directive 2005/32/EC of the European Parliament and of the Council of 6 July 2005* establishing a framework for the setting of ecodesign requirements for energy-using products states, “Energy efficiency improvement — with one of the available options being more efficient end use of electricity — is regarded as contributing substantially to the achievement of greenhouse gas emission targets in the Community.” To implement this directive, the modifications made on the basis of the procedure employed and the measurement results may serve as a model for implementing statutory reductions in domestic utility bills (Léderer, 2010; Horváth, 2002; Gazdasági és Környezeti Minisztérium, 2003).

2. MATERIAL AND METHOD

The main distinctive feature of the measurements carried out to determine potential energy savings was the testing of pumps in situ and in operation, i.e. “on-line”. The most important aim of the measurements is to increase potential savings, given in unit efficiency values measured during the test. The measurement method enables the expected or attainable savings to be modelled with high accuracy.

2.1. Location of experiments

The locations chosen for the experiments were water utility sites serving small and medium-sized towns, where the cost of water supply is highly dependent on the working connections between pumps and network.

Tests were performed on both water supply and wastewater networks.

2.1.1. Water supply stations

- Dombóvár Water Works
- Paks Water Works

2.1.2. Wastewater networks

- Székesfehérvár sewage works and network
- Csákvár network
- Sopron network

2.2. Experimental equipment

The link between water supply rate and electricity consumption formed the basis for proposed modifications to reduce and optimize energy use.

The most energetically economical operation of the pumps was determined for the full range of operating conditions via test measurements using a frequency converter and an ultrasonic flow meter.

The basis of measurement was the instantaneous power consumption of the pump indicated on the frequency converter [kW] and the rate of water flow given on the flow meter [m^3/h]. The relation between these gives the unit energy use in kWh/m^3.

The test involved sequential measurements in which the speed of the frequency converter was continuously changed. Measurements were taken between the limits of 30 and 50 Hz. The minimum frequency is usually determined by the recommendations of the pump manufacturer.

2.2.1 Characteristics of the frequency converter

We used an AQUA DRIVE unit made by DANFOSS. Its characteristics are:

- Measurement range: for pumps operating in the under-10 kW range – usually on water extraction wells – we used the 5.5–10 kW AQUA DRIVE version, and for higher-power pumps, the 50 kW version. To ensure accuracy of measurement, the measurement range of the frequency converter had to match the pump it was controlling. Where frequency converters had already been installed at measurement locations, the existing units were used. These were mostly DANFOSS units. This circumstance is noted in the discussion of each test measurement (DANFOSS, 2006; DANFOSS, 2009).
- Connection to the power supply during measurement was made by temporarily interposing the frequency converter between the pump and the supply. This caused the pump motor to receive the converted frequency. The basic type of frequency converters used in the tests corresponds to that of the converters which may be installed in future, and one was actually installed in Dombóvár during the experiment.
- Where the power rating was greater than 50 kW, the measurement used only built-in units. It is difficult to install a mobile device in this power range.

2.2.2. Characteristics of the ultrasonic flow meter

Water flow through pipes of various cross sections involved in the experiments was measured using the FLUXUS ADM 6725 meter manufactured by FLEXIM (figure 1). Its characteristics are

- suitability for measurement on the pipe types and diameters under examination,
- simplicity and speed of operation in temporary measurement circumstances. It may be used in damp and wet conditions.

Figure 1: Control panel of mobile ultrasonic flow meter used for test measurements

The flow meter measures the flow of liquid using ultrasonic signals and the flow-through method. A transducer on one side of the pipe emits ultrasonic signals, and these are reflected from the opposite side and detected by another transducer (Figure 2). The signals are emitted in both directions (FLEXIM, 2008).

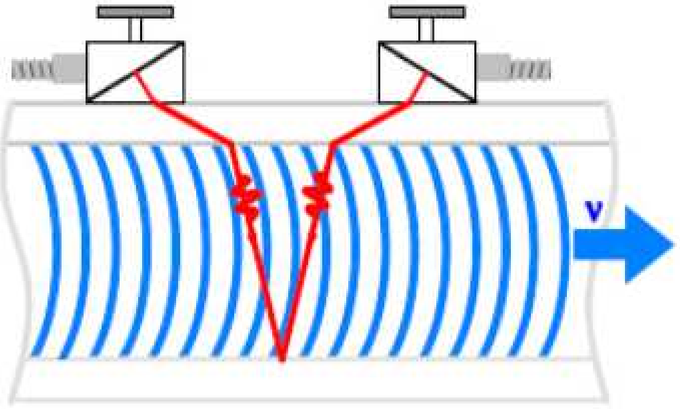


Figure 2: The path of ultrasonic signals in the pipe

Since the medium in which the signals are travelling is in motion, the sound waves have a shorter period of travel in the direction of flow than in the opposite direction. The transit time ΔT may be measured, enabling determination of the average flow speed of the liquid in the path of the ultrasonic signals (Figure 3).

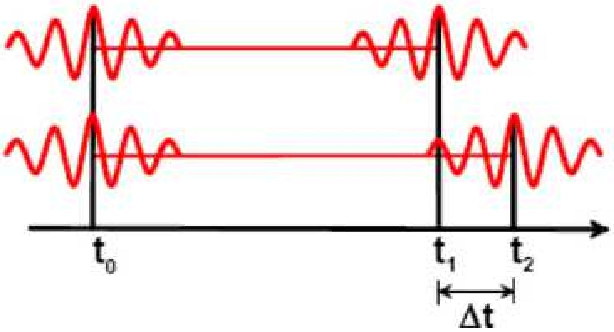
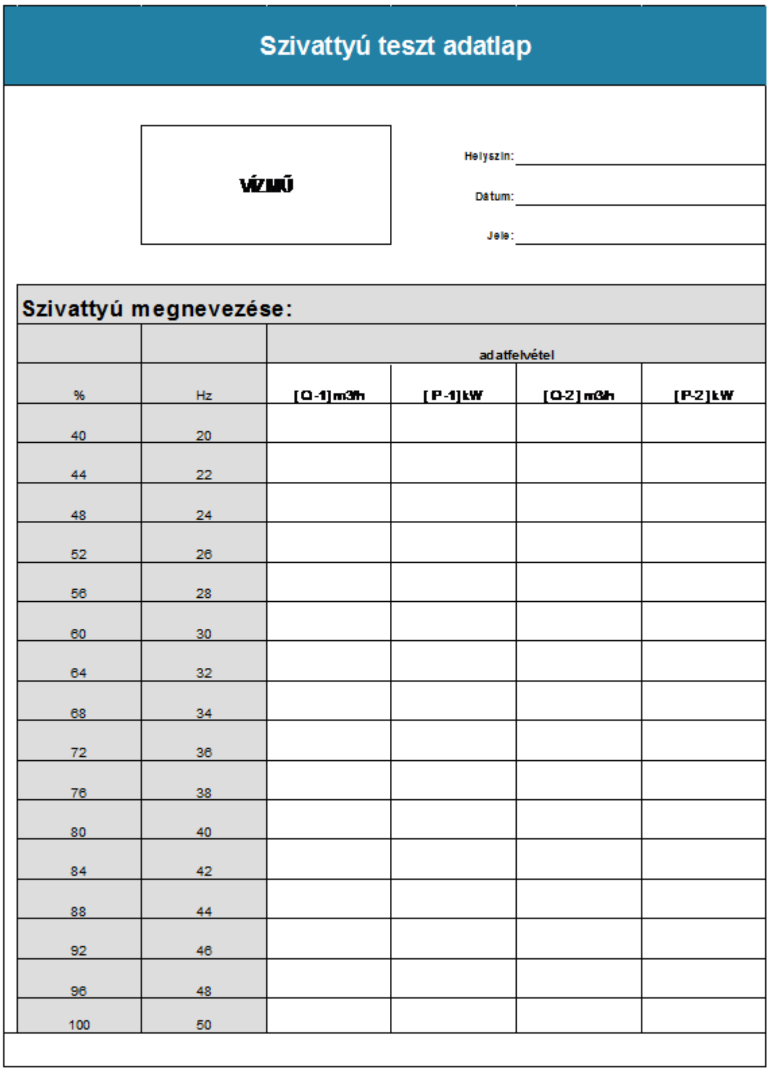


Figure 3: Generation of transit time difference ΔT

The descriptions of each test measurement include analyses of the characteristics which can affect liquid flow as measured, such as the condition of isolation valves. Every setting in the measurement range was recorded on the form shown on Figure 4.



Szivattyú teszt adatlap

VÍZMŰ

Helyszin:

Dátum:

Jele:

Szivattyú megnevezése:

		adatfelvétel			
%	Hz	[Q-1]m3/h	[P-1]kW	[Q-2] m3/h	[P-2]kW
40	20				
44	22				
48	24				
52	26				
56	28				
60	30				
64	32				
68	34				
72	36				
76	38				
80	40				
84	42				
88	44				
92	46				
96	48				
100	50				

Figure 4: Pump test data sheet

2.3 Measurement procedure

We adapted the measurement methods as the Hungarian development partner of the Danish company PICCA (Steffensen, 2011).

The objective of regulation is to attain an optimum state, which occurs when operating near a certain working point. This permits the pumps to be operated with low energy use while satisfying the hydraulic demands (Józsa 2013; MAVÍZ 2010). It does not mean, however, that the pump motor (or the unit as a whole) is operating at its highest level of efficiency, which does not usually coincide with the working point corresponding to water demand. It is only possible to determine the highest-efficiency working point by measurement and control in situ, while the system is in operation.

The purpose of measurements performed on the working system is to determine the point of highest efficiency.

The tests used electronic devices. Measurements were recorded using the Excel program running on a portable computer. Analysis of the data involves individual calculation of unit energy use indicators to create an energy profile. Figure 5 shows a typical energy profile.

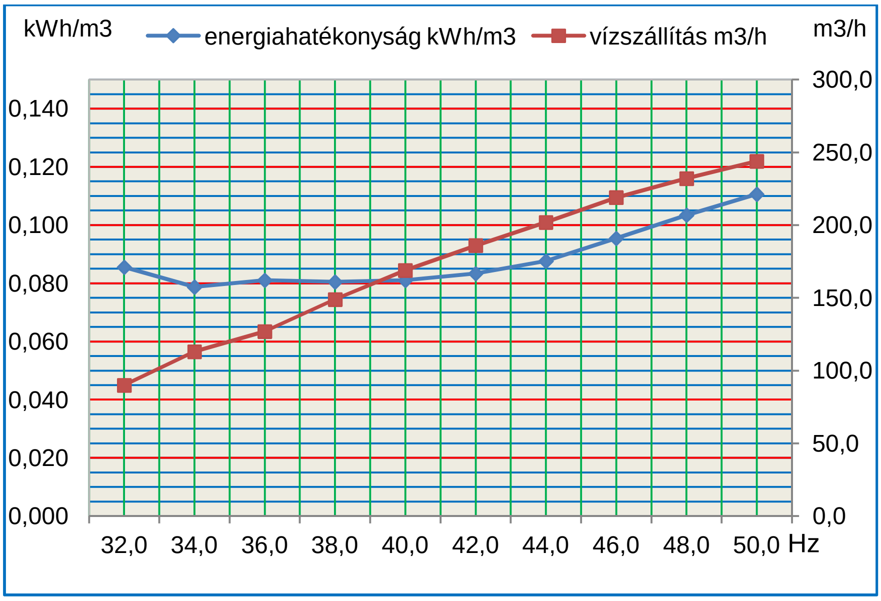


Figure 5: Energy efficiency and water flow test on a pump at motor loads of 32–50 Hz

Operating the pump at the lowest unit consumption achieves the energetically optimum operating condition in every case.

The requirement of highest priority for the water utilities is quantitative provision of service.

Consequently, it is not currently possible to use the optimum setting in every case, and so unit energy consumption cannot always be minimized.

The prescribed water demand is usually higher than the actual demand, so that optimum energy use can only be attained approximately.

The criteria of security of service and optimum energy do not usually coincide in the operations of water utilities.

The purpose of the total test method is to determine the unit energy consumption of the pumps in kWh/m^3 for pumping/transit from point A to point B. The saving in every case is given relative to the 50 Hz value.

The calculated saving depends on the operating parameters. The more precise the available operating data, the more accurately it is possible to calculate the saving, which changes depending on the quantity of water delivered day to day and month to month. The research measurements used “simple optimums”.

The optimum frequency value is not fixed, but constantly changes depending on the number of pumps and/or wells in operation, the specific combinations of these, and the reservoir levels.

The full implementation of this optimum is possible only using control that is optimized for energy efficiency.

When a utility company requests energy efficiency improvement in a system, the tests described in the previous chapter are carried out and the results are analyzed to produce a proposal for energy efficiency.

The calculation based on the test results yields the expected energy savings in the specific system to high precision.

Changes in operating conditions, if they are not radical changes, will cause only small deviations in attainable energy saving during long-term operation. With appropriate IT support, the machinery will always deliver the water so as to meet immediate water demands and will operate in the set range only when operating conditions permit.

2.4. Study of water supply networks

The energy efficiency of water supply networks is characterized by measuring the energy consumption of the system and the utilization of the energy. Systems for small, medium-sized and large towns have different characteristics. There are also major characteristic differences among means of water of extraction. The characteristics of the distribution system (pipe length and diameter, altitude differences, valves, etc.) can crucially affect energy use and thus the expected level of saving. Systems with relatively high unit energy use have greater potential for savings, but this cannot be realized in every case.

2.4.1. Selection of test measurement locations in water supply networks

The type of water extraction is the main consideration, because the conditions of access to the source greatly influence the energy demand. Clearly, extraction from deep drilled wells may require considerably greater energy than from a tapped spring or a karst well or surface abstraction. One of the main criteria for selecting a location is the size of the town it serves, because this determines the water demand.

For the purposes of energy efficiency tests, a small town is one with daily water consumption of less than 800–1000 m^3, and a small water works is one with less than this level of daily extraction. The maximum number of consumers served, if average consumption is 100 l per head of population, is 8–10.000. Industrial consumers can alter these figures.

There are 142 towns in Hungary of population greater than 10,000. I carried out tests in two of these: Dombóvár and Paks, which have populations of 17.017 and 19.481 respectively (KSH, 2014).

Water works of smaller capacities typically supply small towns and villages where there are limited opportunities for energy saving. Some of these water works have very poor unit energy efficiencies. From a strictly energy-efficiency standpoint, savings could best be attained by connecting to another water works if relief and distances permit (Budapest University of Technology and Economics, 2007).

Both surface and underground extraction offer possibilities for test measurements. Careful consideration is required to decide the test approach for special underground modes of extraction, such as radial collector wells and riverside and riverbed galleries (Karácsony and Mészáros, 1998). Since water levels vary over several metres, the unit efficiency of the pumps also changes, making regulation difficult.

Good subjects for testing are deep drilled wells and the associated water works, and extraction from karst wells.

For unmodified pipe networks, optimizing or possibly replacing pumps can reduce operating and consumer costs.

Factors other than pump characteristics are:

- Location of extraction,
- Necessity for treatment,
- Mode of extraction,
- Connection to the network.

All of these factors offer opportunities for cost reduction, but exploiting some of them may be excluded or restricted if the system constraints cannot be changed. Where wells operate continuously 18–20 hours per day and/or with motors running at less than 3.5 kW, there is little scope for reducing their unit energy consumption.

Where the water is treated, the process requirements set a constraint on the regulation of the pumps supplying the filters: e.g. high filter pressure or volume of the raw or treated water reservoir.

By contrast, pumps which fill reservoirs, high-point tanks and water towers, and whose systems of connection serve several functions, have important roles.

2.4.2. Selection of Dombóvár Water Works

In terms of type of extraction, mode of operation, and rate of extraction, Dombóvár Water Works (Figure 6) was ideal for test measurements and subsequent experiments. The results bore this judgement out.

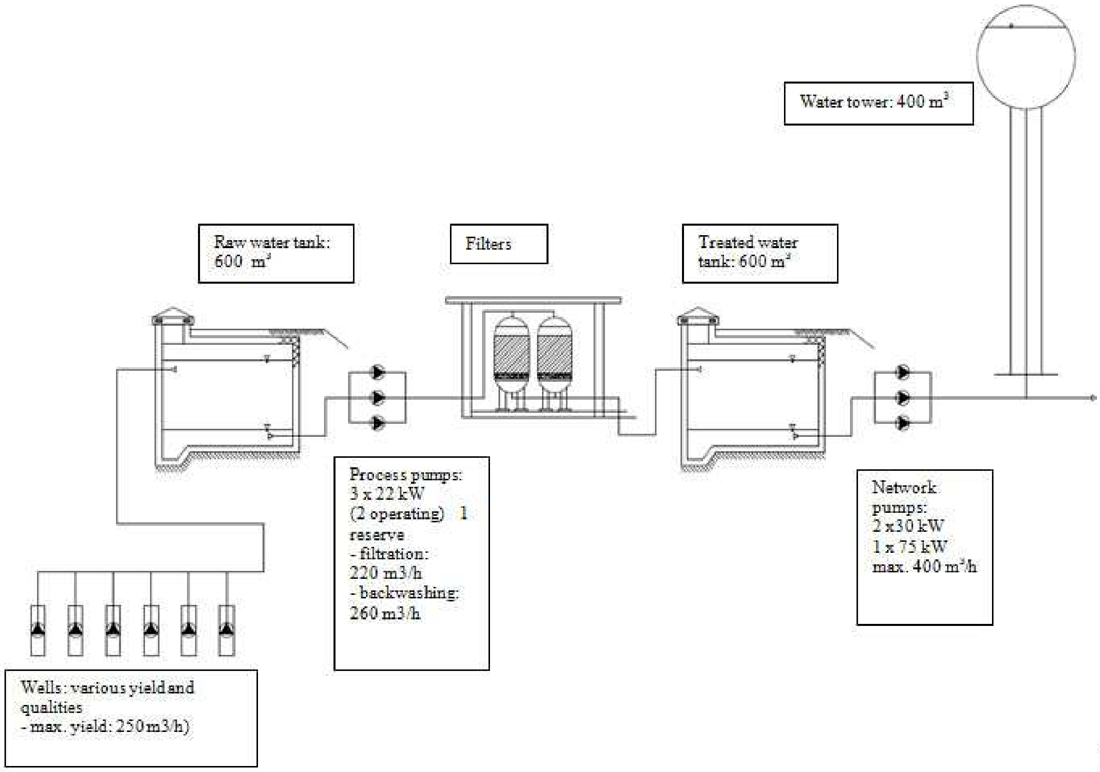


Figure 6: Process diagram of Dombóvár Water Works

The water works operates on two sites and serves the town of Dombóvár and some neighbouring villages. The installed capacity permits uninterrupted water supply in case of failure of a well or pipe fracture in the system. The water works has around 20.000 consumers. It supplied water at the annual quantity of 1.200.000 m^3 between 2008 and 2012, the period of test measurements and evaluation. Water extraction is solely from deep-bored wells, like most water works of similar size in Hungary.

2.5. Study of sewage systems

Our study concerned sewage systems where pumps carry wastewater and rainwater into a common sewer and into treatment works. The study did not cover the pumps involved in sewage treatment, since they are regulated as part of the treatment process. The higher the power consumption of a sewage pump, the greater the potential saving. This saving, however, cannot always be attained.

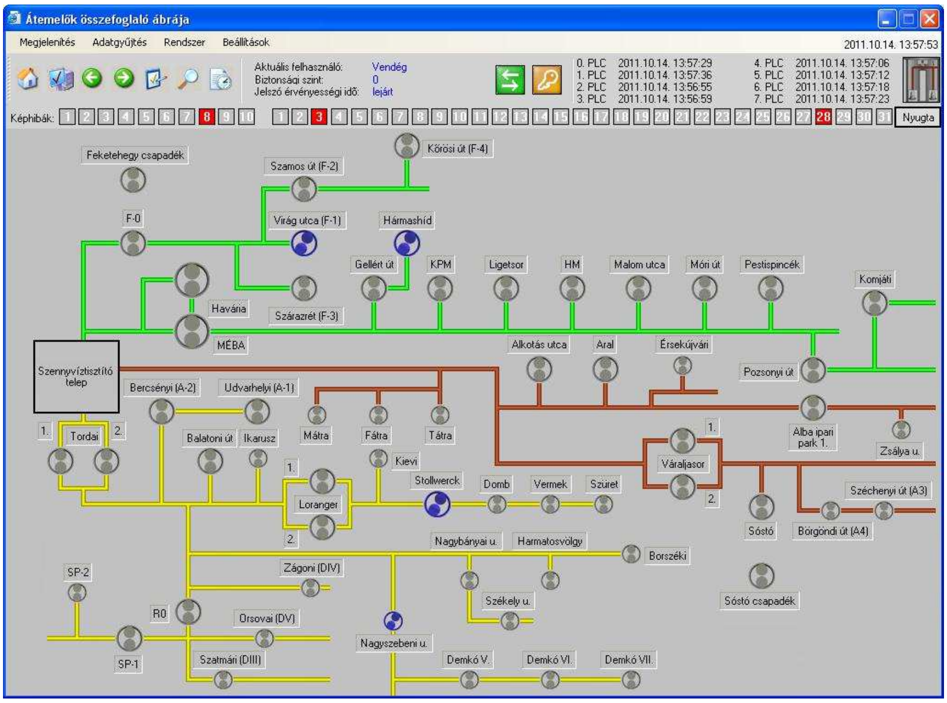
2.5.1 Selection of test measurement locations on sewage systems

For measurements of energy efficiency on the pumping of sewage, the subjects of testing are the pumps themselves. Under normal working conditions, where a town is served by a separate sewer, the quantity of wastewater transported by the pumps is approximately the same as the quantity of water supplied (Juhász 2008). (Normal working conditions means absence of infiltration and incorporation of rainwater.) As for water supply systems, we regard small towns as those with consumption of less than 800–1000 m^3/day. The sewage collection and pumping system is of a character that requires small pumps with limited scope for energy saving.

Sewage works are usually located at a low-lying point to take advantage of gravitational drainage potential. The wastewater collected there requires to be pumped into the treatment works by final wastewater pumps. We calculated that there is potential for saving where at least 1000 m^3/day has to be pumped. Smaller pumps consume so little power that the probable saving would not cover the investment required to obtain it.

There are limited means for measuring the rate of wastewater flow through sewage pumps. For small towns, flow is measured only at the final wastewater pumps to check the quantity arriving at the sewage works. Flow measurements are more common, but not universal, at large sewage pumps in the systems of medium-sized towns. Consequently, the running time and the power consumption as calculated from nominal power constituted a reliable basis for selecting pumps on which measurements were to be performed. This enabled a check of whether savings could be expected from the way the system operates. Sewage pumps are chosen to be able to meet the peak loads that arise locally. Peak loads usually occur at times of high precipitation. The peak demand is usually several times the power required for transporting wastewater under normal conditions, and to meet it, there are usually at least three pumps installed in the pumping station (of which one is a reserve). These pumps are often of different rated power. Such configurations have considerable potential for saving in normal, dry-weather operation.

These considerations all had significance in the Székesfehérvár sewage system for the testing of sewage pumps.The process diagram of the Székesfehérvár pumps is shown in Figure 7.



2011.10.14. 13:57:53

Aktuális felhasználó: Vendég
Biztonsági szint: 0
Jelszó érvényességi idő: lejárt

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0. PLC   2011.10.14. 13:57:29     4. PLC   2011.10.14. 13:57:06
1. PLC   2011.10.14. 13:57:36     5. PLC   2011.10.14. 13:57:12
2. PLC   2011.10.14. 13:56:55     6. PLC   2011.10.14. 13:57:18
3. PLC   2011.10.14. 13:56:59     7. PLC   2011.10.14. 13:57:23
```

Figure 7: Process diagram of sewage pumps and system in Székesfehérvár

The existing instrumentation is very important for the test measurements, particularly for the accuracy of water flow measurement. Built-in and regularly-calibrated flow meters greatly facilitate measurements and increase their reliability. Flow-through meters are rarely used for wastewater, however, and portable flow meters usually had to be installed for the period of the tests. The optimum location for measurement at the pumps had to be chosen carefully in accordance with the manufacturer’s instructions for the meter, and checked by visual inspection while planning the test. The research involved measurements on both types of sewage pump.

The Székesfehérvár sewer and its pumps had been regularly renovated, but before the present study, there had been no specifically energy-optimization tests or developments on the pumps. The system thus offered a promising subject for a sewage pump energy saving potential study in a large Hungarian town. Pumps in the system of rated power greater than 22 kW were designated for measurements.

The relatively long pressurized pipes required the installation of high-power pumps. For these, large savings can be made even where the saving potential is relatively small (a hypothesis proven by subsequent measurements). The pumps are described in detail together with the measurements. All of the tests were carried out using a portable flow meter.

Our calculation of financial savings was based on the average unit cost of electricity paid by the water works, HUF 36 Ft/kWh (ex. VAT).

3. RESULTS

3.1. Results of tests on water supply networks

Dombóvár

There are two water works supplying water to Dombóvár and surrounding villages. These, with their wells, filters and pressurizing pumps, are shown on Figure 6.

We started measurements for the study in 2008. The water extracted is filtered at the water works. From there, booster pumps pass the water either directly to the network or to a water tower. The water supply is relatively constant and the water quality fully meets the requirements. Both water extraction sites were involved in the study. They are designated (in order of measurement) site V and site IV.

Water works site V

There are two deep drilled wells serving the site, designated N2 and N5. N2 is located outside the site, and N5 inside it.

Optimization of deep drilled well N2: N2 connects to the site via several kilometres of pipe. We performed 14 measurements for the study. The energy profile of the results is shown on Figure 8.

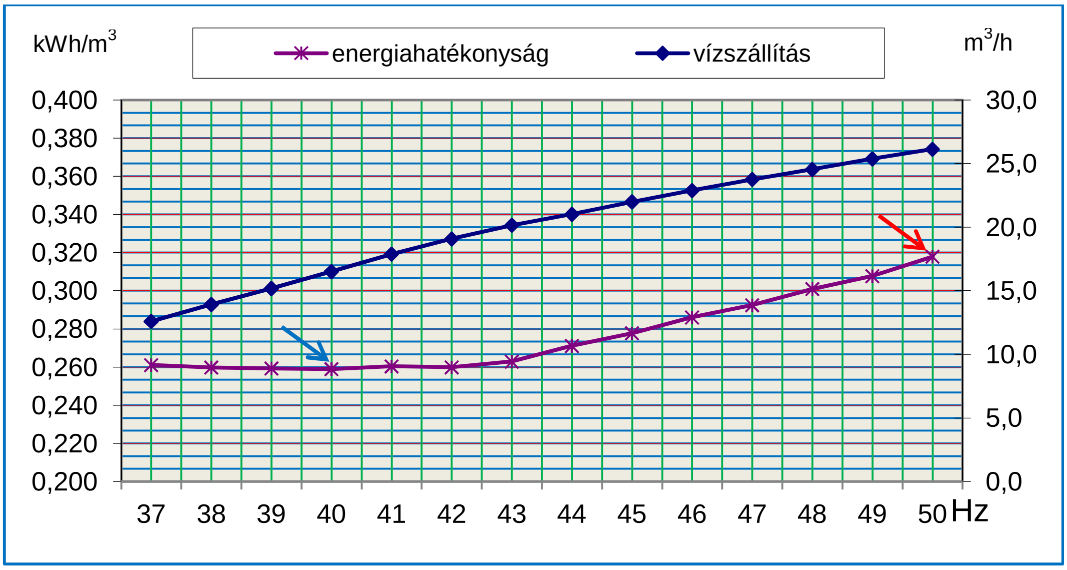


Figure 8: Energy efficiency and water transport of pump M2 at motor loads of 37–50 Hz

Energy profiles and their implications

Measurements were performed starting with electrical power supplied at a frequency of 50 Hz and reducing by 1 Hz steps to 37 Hz. On Figure 8, the results are thus ordered right to left (50–37 Hz). The unit energy consumption (purple line) in kW/m^3 shows a steady decrease (greater efficiency), and water flow (blue line) in m^3/h also steadily decreases. The most economical consumption figure is where the pump can extract the same daily amount of water from the well as before but consume less electricity in doing so. In this mode of operation, it will extract the water over a longer period.

The following values may be read off Figure 8: The least economical unit energy consumption was 0.318 kWh/m^3, measured at 50 Hz (red arrow on Figure 8).

The most economical unit energy consumption was 0.259 kWh/m^3, measured at 40 Hz (blue arrow on Figure 8). The difference between the two (rounded) was 18%.

By regulating extraction from the well to maximize energy efficiency for unchanged daily water quantity, the following could be achieved.

With the most economical mode of operation, the expected annual saving is approximately 10.000 kWh, which will reduce carbon dioxide emissions by about five tonnes.

The total potential savings over the 12-year lifetime are approximately 125.000 kWh of energy 62.5 tonnes of emitted carbon dioxide. Both of these figures imply major environmental benefits.

The discussion of the other measurements incorporates the same principle, and the analysis is given only if there is a deviation.

Optimization of well N5

The deep drilled well N5 is located on the water works site. Some measurements in the series had to be repeated because of multiple pump shutdowns. These were later found to have occurred because the state of wear of the pump. These interruptions account for the unevenness of the energy profile. The energy profile obtained from the measurements is shown in Figure 9.

The least economical unit energy consumption was 0.455 kW/m^3.

The most economical unit energy consumption was 0.352 kW/m^3.

The difference between them (rounded) was 23%.

The saving cannot be maximized, because the well must deliver 350.000 m^3/year, while the optimum power consumption would deliver only 235.000 m^3/year.

The 10% savings potential at this well translates to an annual saving of 15.000 kWh in energy and 7.5 tonnes in carbon dioxide emissions.

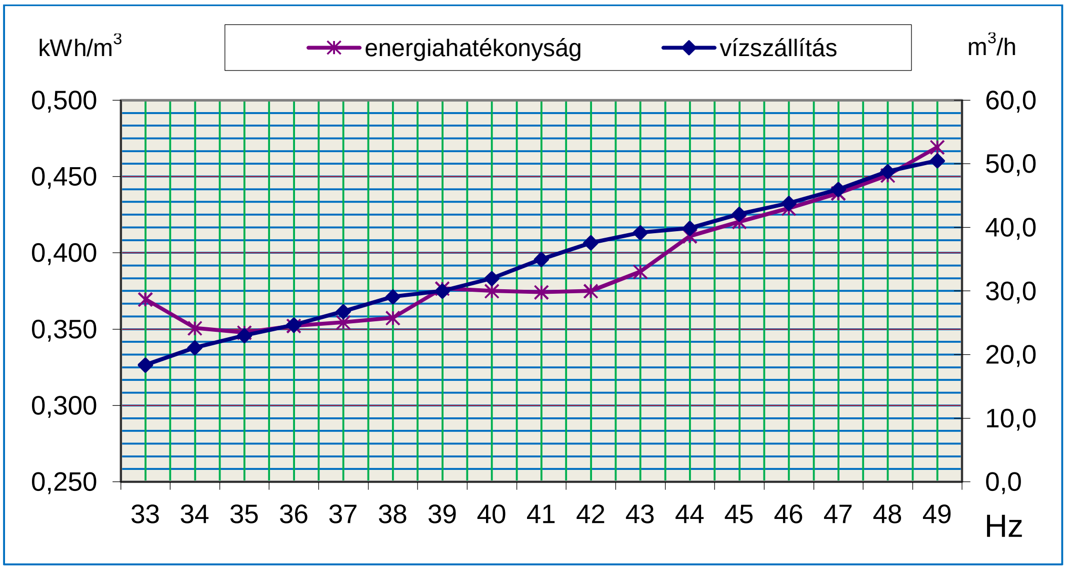


Figure 9: Energy consumption and water transport of well N5 at motor loads of 33–49 Hz

This is a major saving in terms of the analysis and evaluation of environmental factors. Over a period of 12 years, these result in an overall saving of 187.000 kWh in energy and 93.5 t in carbon dioxide emissions.

Pumps in the water supply network

We carried out tests on three pumps: SZ4, SZ6 and SZ7. These are located in pumping stations outside the water works.

The test measurements were preceded by a survey of the existing condition. Overall, the parameters of the condition of the pumps were very good, which enabled the test measurements to be carried out quickly and productively.

The measurements yielded the energy profiles shown on Figure 10. For the sake of comparability, this figure does not show the water transport data.

The pumps were connected as follows for the operational tests:

- Measurement 1 – pump SZ6 only
- Measurement 2 – pump SZ7 only
- Measurement 3 – pumps SZ6 and SZ7 together
- Measurement 4 – pump SZ4 only

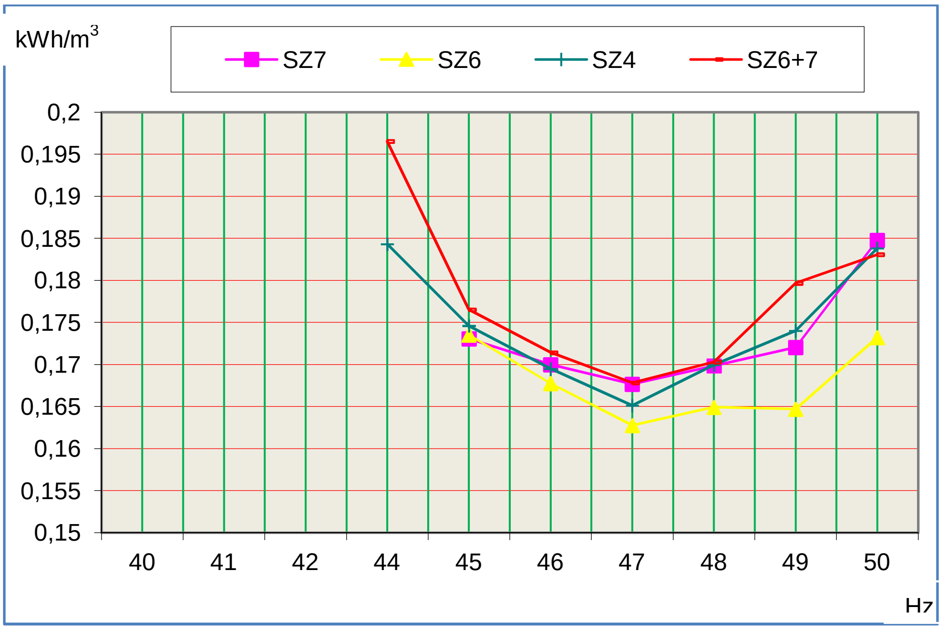


Figure 10: Energy consumption of water supply pumps SZ4, SZ6 and SZ7 at motor loads of 44–50 Hz.

The test data showed that pumps in these combinations (SZ6 alone, SZ7 alone, SZ6 and SZ7 together and SZ4 alone) operated at approximately equal efficiencies. The least economical unit energy consumption for all four pumps was 0.184 kWh/m^3.

The most economical unit energy consumption was 0.165 kWh/m^3.

The difference between the power consumption in the two modes of operation was 0.019 kW or approximately 10%.

The annual energy saving attainable for each pump with the parameters set to provide the most economical mode of operation would be 17.000 kWh and the annual carbon dioxide emissions saving would be 8.5 tonnes. There would also be an annual saving of 6.500 working hours for the pumps taken together. In the longer term, 12 years, there would be savings of 204.000 kWh of energy and 102 tonnes of carbon dioxide emissions.

Pump house pumps

The water supply pumps SZ1, SZ2 and SZ3 are located in pump houses on the water works site. All have the same parameters and installation. Test measurements were carried out only on pump SZ1, but the results yielded valid conclusions for the operating environment of the other pumps. All of the test measurements provided significant data.

The measurement design had to account for the operation of the pump with a partially-closed gate valve. The operator employs this arrangement if the design working point of the pump significantly deviates from the working condition. This was taken as the basis state for calculation of potential saving. Figure 11 shows the energy profile obtained from the measurements.

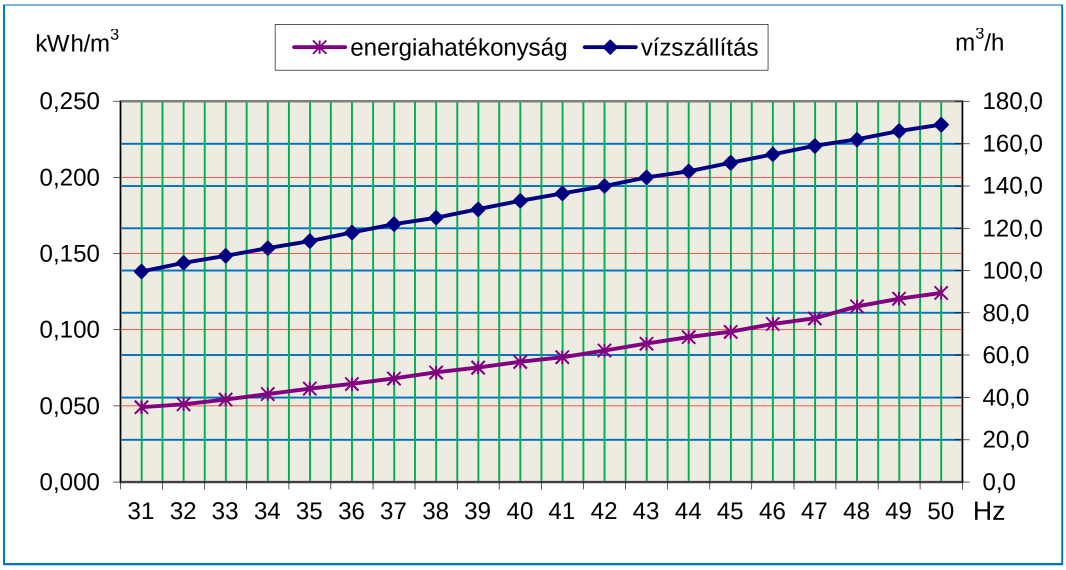


Figure 11: Energy consumption and water transport of supply pumps SZ1, SZ2 and SZ3 at motor loads of 31–50 Hz.

The least economical unit energy consumption of pump SZ1 was 0.124 kWh/m^3.
The most economical unit energy consumption of pump SZ1 was 0.044 kWh/m^3.
The difference between the least and most economical power consumption levels was 0.080 kW or 65 %.

However, consideration of the other service parameters of water quality requirements and quantitative requirements for security of supply reduces the saving to 35%. At this level, the annual saving would be 55.000 kWh. Calculating at an average of HUF 34 / kWh, this is equivalent to an annual saving of HUF 1.9 million. The annual reduction of carbon dioxide emissions is also significant – 27.6 tonnes.

Taking these figures together, the optimized condition clearly implies more economical and environmentally-friendly operation.

The study results also indicated further efficiency improvement with the joint operation of two pumps, SZ1 and SZ2. This has the potential to save 65 % of energy consumption. The annual saving would be 80.000 kWh, or (at HUF 34 / kWh) HUF 2.7 million. Carbon dioxide emissions would decrease by 40 t. For a lifetime of 12 years, the energy saving would be 990,000 kWh or – with an annual saving of 55.000 kWh – 650.000 kWh.
There would also be substantial reduction of carbon dioxide emissions: 325–495 tonnes.

Characteristics of Water Works site IV

Site IV of the Water Works was also included in the study. There, we optimized one deep-bored well (3A) and one water supply pump (SZ1).

As for the other measurements, we used a portable DANFOSS frequency converter and, for the well, a flow-through meter.

Characteristics of deep drilled well 3A

The well lies on the water works site. A special feature of its operation is that, owing to its low yield, it operates almost continuously. Its operating characteristics are shown on Figure 12.

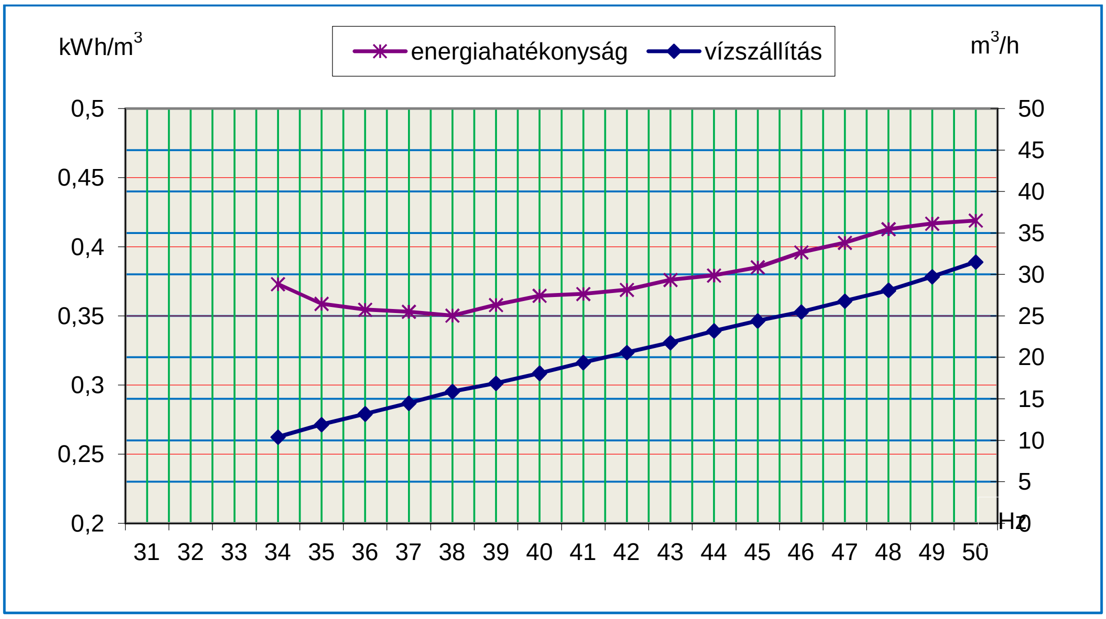


Figure 12: Energy consumption and water transport of well 3A at motor loads of 34–50 Hz

The measured energy profile shows that the least economical energy consumption was 0.419 kW/m^3 and the most economical, 0.353 kW/m^3. The difference between the two, rounded, was 15%.

Although this implies some energy saving potential in principle, it cannot be practically attained in the present situation. This is because operation at the optimum point would require a yield of 16 m^3/h instead of the present 32 m^3/h. This shortfall could not be made up from other wells. There could only be a saving if water was extracted from more than one deep drilled bored well. At my recommendation, a new well was indeed drilled (see chapter 4.4.1).

Tests on pumping station pumps

Two pumps in the pumping station, SZ1 and SZ2, were subjected to tests. The measurements did not have to take water quality and quantity parameters into account, but only the potential saving. The results showed that savings were attainable.

The tests on pump SZ1 served as a model. Previous experience of reserve pumps implied that SZ2 would give the same results. The pump operated with a partly-closed gate valve. The measurement results are shown on Figure 13.

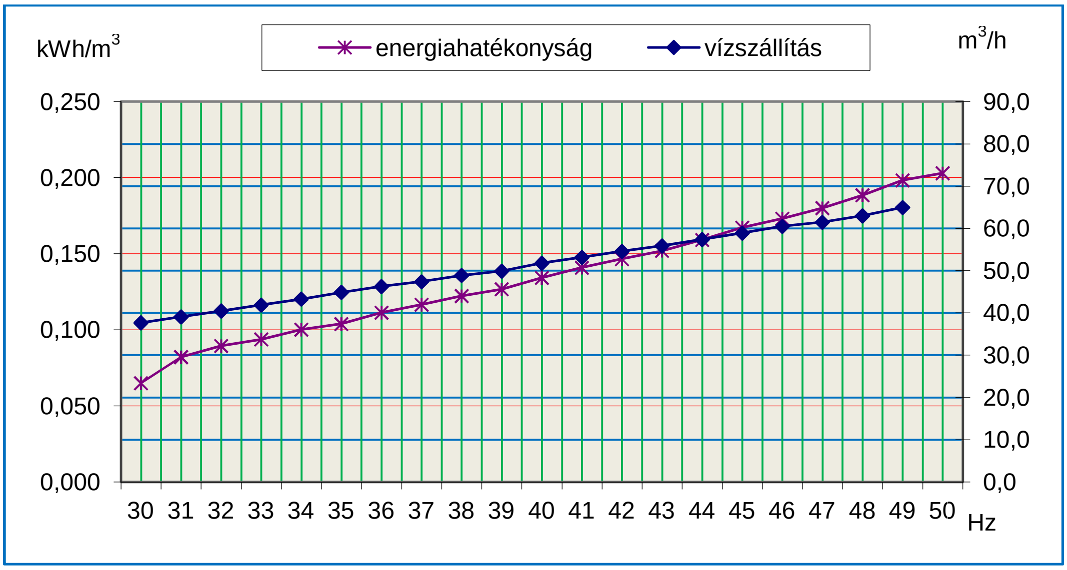


Figure 13: Energy consumption and water transport of water supply pump SZ1 under motor loads of 30–50 Hz.

The least economical unit energy consumption was 0.203 kWh/m^3.

The most economical unit energy consumption was 0.058 kWh/m^3.

The difference between the two was 68 %.

The annual savings if the full potential is attained would be 55.000 kWh and ~ 27.5 t CO_2, with a total of 6.500 running hours.

The potential saving is 70%, depending on running hours.

Owing to the mode of installation of their discharge tubes, operating the two pumps together in this case would not change the result.

The savings over a lifetime of 12 years would be about 660.000 kWh or ~ 330 t CO_2 / year.

Optimization of Dombóvár water supply

Energy could be saved at both water works sites by proper regulation. For the deep drilled wells, this would also improve the operating conditions because there would be less load on both wells (over a longer period), increasing their lifetime.

The measured potential savings range between 15 and 60%. The total attainable saving calculated from the measurements is 137.400 kWh/year (11.450 kWh/month) or HUF 3.570.000/year. The attainable reduction in CO_2 emissions is 76 t/year and 900 t for the specified lifetime of 12 years.

Proposed improvements and additions at water works site V

The pumping station pumps offer considerable savings potential, and the measurement results clearly show that the pumps are capable of optimized operation.

The potential savings for the network pumps is lower, but optimization of pump operation could still provide benefits.

The savings potential at the wells is even lower, and the payback period is relatively long. Renovation of well **N5** (with frequency converter and motor starter) would provide the expected result, and was definitely recommended. I reached similar conclusions for the other wells on the site. The test measurements clearly showed that optimizing the pumps accordingly would save energy under unchanged conditions of supply.

Proposed improvements and additions at water works site IV

Considerable saving was attainable with the pumping station pumps, and optimizing their operation was definitely recommended.

A new well is being planned to meet rising quantitative demand and to improve water quality. If it is built, we recommend it is optimized together with the existing well.

3.2. Pumped wastewater networks

Székesfehérvár pumping station Tordai-2

This pump was tested to determine the optimum working condition and the potential savings. The same principle was followed with the other wastewater pumps, but their descriptions mention only the differences. The station transports wastewater to the treatment plant via several kilometres of pipe. The operating data of the Tordai wastewater pumping station are given in Table 1.

Table 1: Tordai wastewater pumping station operating data

Pumping station:	**Tordai-2**
Number of pumps:	2
Flow measurement:	At wastewater treatment plant
Control:	Other PLC, level control
Water transport (m^3) 2010:	598 773

Pump number:	**1.**	**2.**
Power (kW):	22	22
Mode of starting:	Direct	Direct
Daily operating hours:	5.30	4.70
Annual operating hours:	1933	1716

The controller switches between the two 22 kW pumps, ensuring approximately equal operating time. The two pumps are of the same type and use the same motor. The water flow was determined during the test using the built-in flow meter.

The water level when the measurement was taken was allowed to reach a high level – almost 100% – so that we could carry out the measurements continuously. The high water level resulted in water transport in the test pump of 244 m^3/h at 50 Hz, considerably higher than the average value given in Table 2, calculated from the hours run: 164 m3/h with direct start. (Total water transport in 2010: 598.773 m^3 / 365 days = 1640 m^3/day / 10 hours total operating time = 164 m^3/h average water transport.)

In terms of energy efficiency, this difference shows that the pumps may be operated much more efficiently at high sump levels. We did not carry out tests to determine the variation of efficiency with sump level.

Test data from pump 1

The measurements shown on the graph of Figure 14 were performed in steps of 2 Hz downwards from 50 Hz, i.e. from right to left.

The least economical energy consumption was 0.111 kWh/m^3, measured at 50 Hz, and the most economical consumption 0.081 kWh/m^3, at 36 Hz (marked with the red arrow on Figure 14). The potential saving implied by this difference is 26.7%. The water transport at the most economical energy consumption is 125 m^3/h (the water yield at measurement 8, marked on

Figure 14 with the blue arrow). To provide this yield, both pumps would have to operate 13.4 hours per day to transport the required 600,000 m^3/year to the treatment plant (13.4 h/day x 125 m^3/h x 365 days/year=611.375 m^3/year). Figure 14 shows the unit values calculated from the measurements.

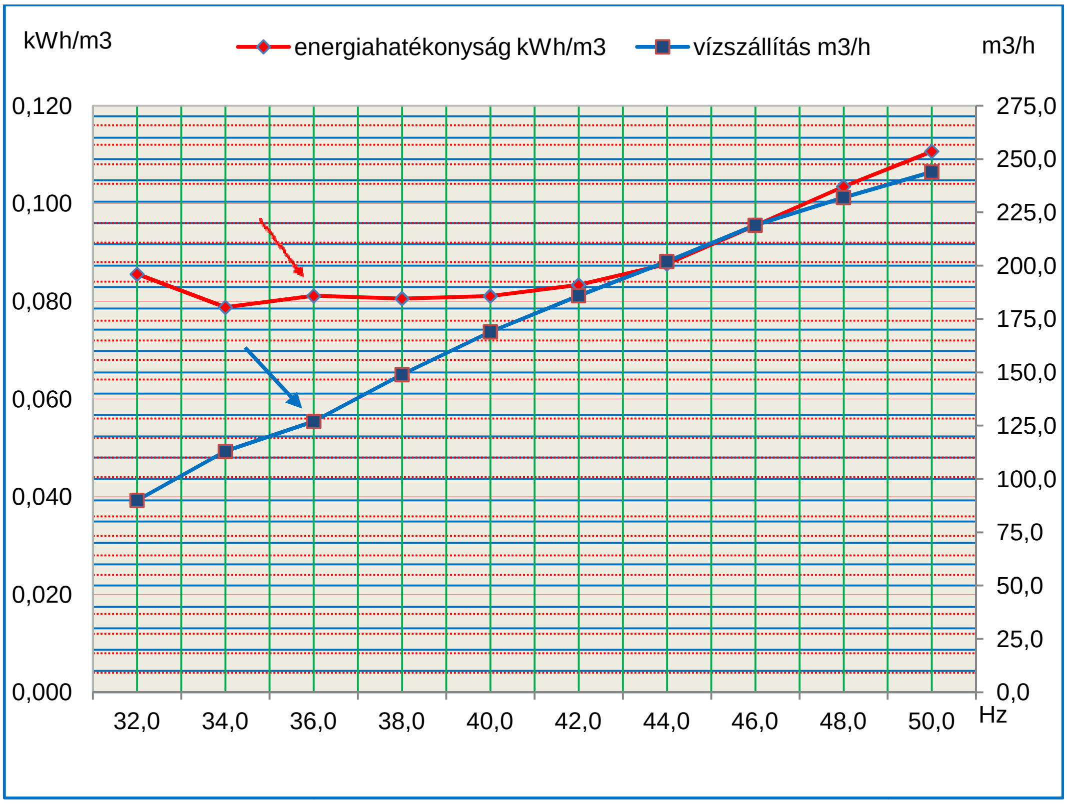


Figure 14: Energy consumption of Tordai wastewater pump at motor loads of 32–50 Hz

To optimize the annual transport of 600.000 m^3 of wastewater, currently performed by operating the two pumps seven hours per day, they should be run at increased water level for 13.4 hours per day.

The period of optimum operation of the pumps was estimated to be 85% of total operating time. No saving was calculated for the remaining period.

Table 2 summarizes the attainable savings and their associated unit values.

Table 2: Savings calculation for Tordai-2 wastewater pump

		kWh/m3	**Saving**		**kWh**	**TON CO2**
Energy consumption	before	0.111			68.985	34.5
	after	0.081	26.7%		50.561	25.3
			Economy			
		kWh	**Potential**	**kWh**	**HUF**	**TON CO2**
Annual saving	1	18.424	85%	**15.661**	**563.779**	9.21
Savings over x years	6	110.545		**93.9635**	**3.382.677**	47
Years of saving over x years				**1.6**		

Calculated at 36 Ft/kWh, the attainable annual savings are HUF 560.000 and 9 t of CO_2 emissions.

The energy saving under actual operating conditions could vary slightly from this prediction.

Test of pumps in the MÉBA station

The pumping station transports wastewater to the treatment plant via several kilometres of pipe.

The operating data of the pumping station are shown in Table 3.

Table 3: MÉBA wastewater pumping station operating data

MÉBA

Number of pumps:	3
Flow measurement:	Out of service
Control:	Other PLC, level control
Water transport (m^3) 2010:	2.242.747

Pump number:	**1.**	**2.**	3.
Power (kW):	44	44	44
Mode of starting:	Direct	Direct	Soft start
Daily operating hours:	3.56	3.12	3.33
Annual hours run:	1300	1138	1214

The controller switches between the three 44 kW pumps, ensuring approximately equal operating time. The water in the sump was at the operating level during the measurement. Water flow was measured using a portable flow meter. The three pumps are of the same type and use the same motor. The figure taken for annual water transport was 2.243.000 m^3.

In the present operating conditions, the annual transport of wastewater is attained under present operating conditions using the three pumps at 10 operating hours per day, and in the optimum condition at 18.6 operating hours per day. Peak periods had to be taken into account.

Operating characteristics of pump 3

The least economical energy consumption was 0.073 kWh/m^3, and the most economical, 0.058 kWh/m^3. The difference between these implies potential saving of 26.7%. The unit values of the measurement are shown on Figure 15.

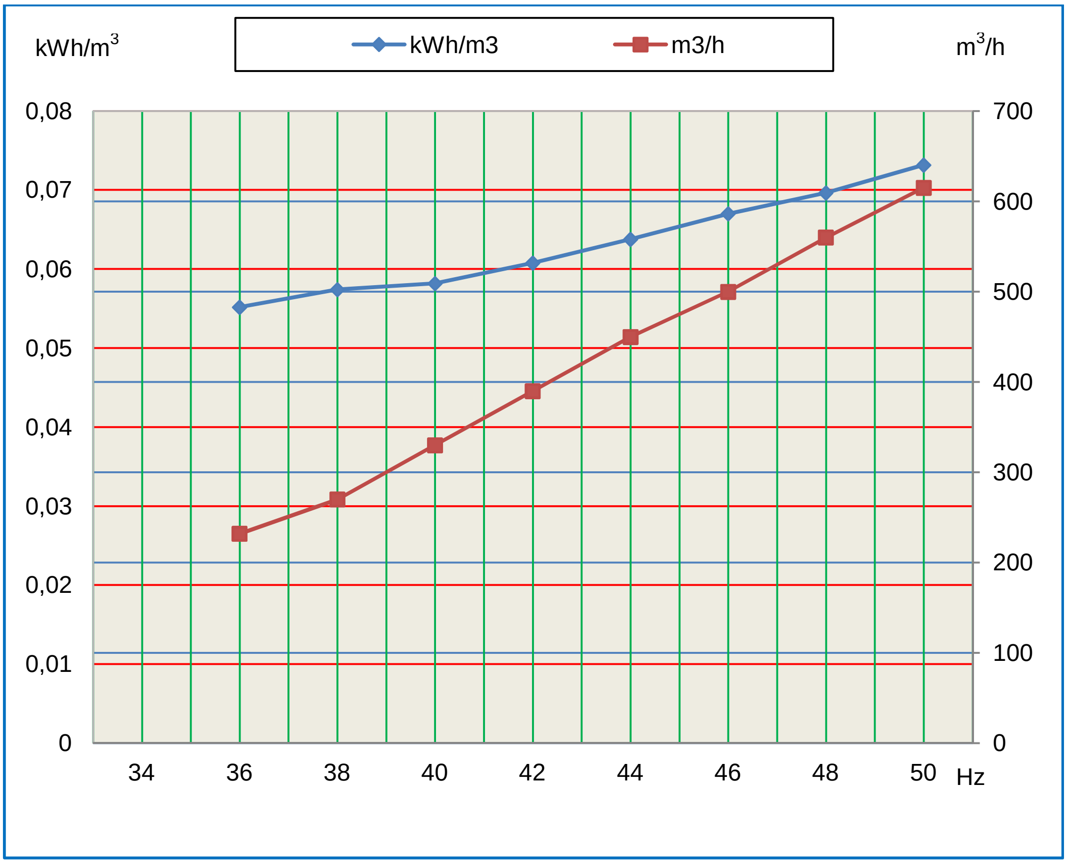


Figure 15: Energy consumption and water transport of wastewater pump MÉBA at motor loads of 36–50 Hz.

The period of operation in the optimum mode was estimated at 85% of total running time. No saving was calculated for the remaining period. Table 4 summarizes the attainable savings and their associated unit values.

Table 4: Savings calculation for MÉBA wastewater pump

Calculated savings						
		kWh/m3	**Saving**		**kWh**	**TON CO2**
Energy consumption	before	0.073			164.250	82.1
	after	0.058	20.5%		130.604	65.3
Economy						
		kWh	**Potential**	**kWh**	**HUF**	**TON CO2**
Annual saving	1	33.646	85%	**28.599**	**1.029.579**	16.82
Savings over x years	6	201.878		**171.596**	**6.177.472**	85.8
Years of saving over x years				**1.23**		

Calculated at 36 Ft/kWh, the annual savings attainable are HUF 1.100.000 and 17 t of CO_2 emissions.

The energy saving under actual operating conditions could vary slightly from this prediction.

Optimization of pumps in Váralja sor pumping stations I and II

The twin wastewater pumps in Váralja sor supply wastewater to the central reservoir of the sewage treatment plant.

The initial data are given in Table 5. This pumping station uses the “twin pumping station” arrangement. The 30 kW pump in station 1 is effectively unused, while the two 15.8 kW pumps in station 2 are both operated, sometimes at the same time. The two stations are linked by pipes and isolated in the present operating configuration. It is technically possible to swap operation of the two stations, enabling comparison of the pump efficiencies.

The pumping stations transports wastewater to the treatment plant via a relatively long pipe (several kilometres).

Adding up the running hours of the 15.8 kW pumps gave the figure of 8.6 hours. Water flow was measured using the built-in meter. For the 30 kW pump, which has no flow meter, we used a portable flow meter.

To optimize the annual transport of 350.000 m^3 of wastewater, currently performed by operating the 15.8 kW pumps in pumping station 2 for 8.8 hours per day, the 30 kW pump in pumping station 1 should be run for 6.5 hours per day. Peak periods must be taken into account.

Table 5: Váralja sor wastewater pumping station operating data

Pumping station:	**Váralja 1**	**Váralja 2**	
Number of pumps:	1	2	
Flow measurement:	none	yes	
Control:	Other PLC, level control	Other PLC, level control	
Water transport (m^3) 2010:	n/a	Water transport (m3) 2010:	348.300

Pump number:	**1.**	**1.**	**2.**
Power (kW):	30.0	15.8	15.8
Mode of starting:	Direct	Direct	Direct
Daily operating hours:	0.13	4.30	4.53
Annual operating hours:	48.81	1570	1655

The least economical unit energy consumption of the 15.8 kW pump was 0.144 kWh/m^3. The near-optimum consumption of the 30 kW, measured at 32 Hz, was 0.051 kWh/m^3.
The potential saving deriving from the difference between these two (rounded) was 64%.

The measurement figures of the 15.8 kW pumps Sz.2 and Sz.3 are shown on Figure 16/I. It is clear that the least efficient energy use occurs when the two smaller pumps operate together (red curve). One pump operating (blue curve) is less inefficient. These two curves show that the optimum figure is obtained at full motor load. The larger pump, no. 1, can operate much more efficiently in a lower speed range. Since its rate of transport is much higher – 150 m^3/h at the optimum 32 Hz – it can perform the task in much fewer operating hours. The test results are shown on Figure 16/II.

The period of the optimum operating mode was estimated as 85% of total operating time. We did not calculate a saving for the remaining period. Table 6 summarizes the attainable savings and the associated unit values.

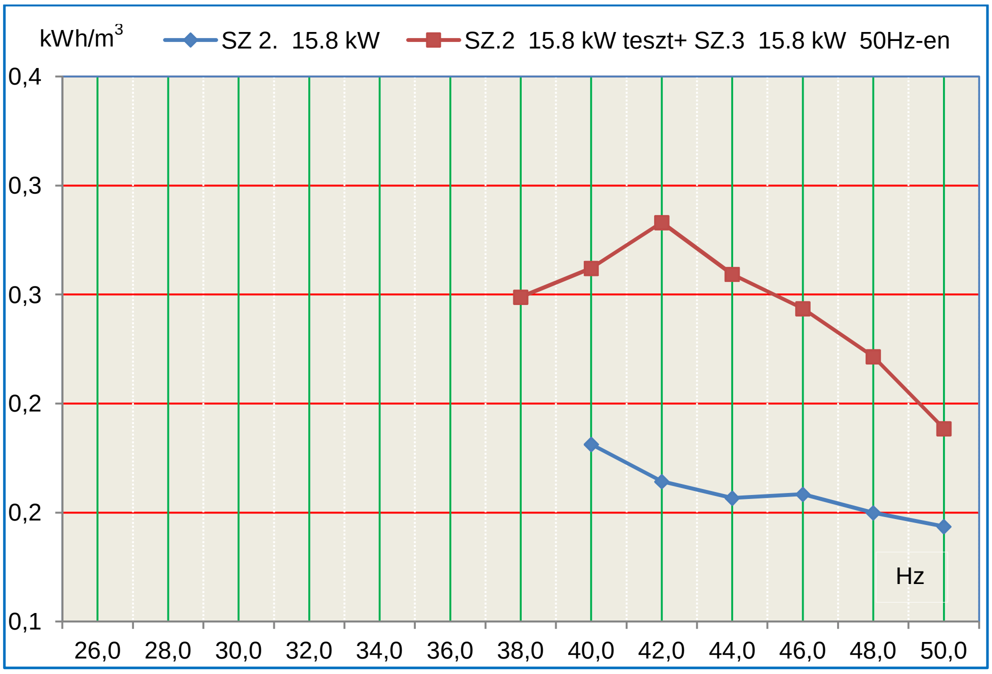


Figure 16/I.: Energy consumption of wastewater pumps Váralja sor Sz.2 and Sz.3 at motor loads 38–50 Hz

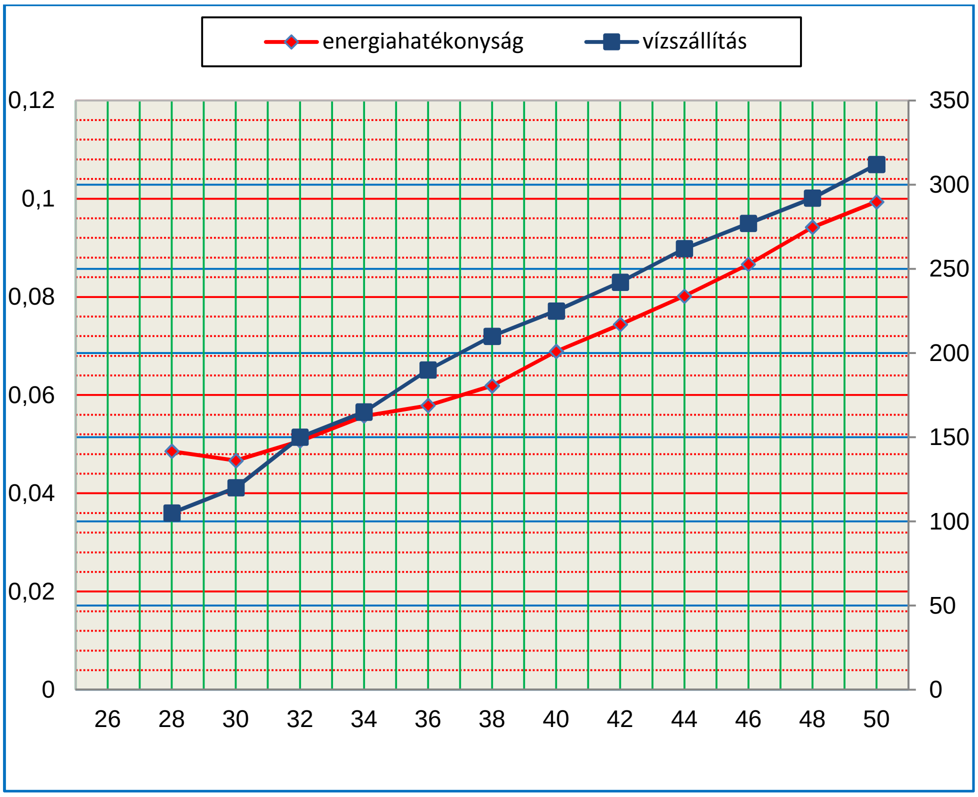


Figure 16/II.: Energy consumption of wastewater pump Váralja sor **Sz.1** at motor loads 28–50 Hz.

Table 6: Calculation of savings for Váralja sor wastewater pump

Savings calculation						
		kWh/m3	**Saving**		**kWh**	**TON CO2**
Energy consumption	before	0.144			50.750	25.4
	after	0.051	64.7%		17.902	9.0
Economy						
		kWh	**Potential**	**kWh**	**HUF**	**TON CO2**
Annual saving	1	32.848	85%	**27.921**	**1.005.150**	16.42
Savings over x years	6	197.088		**167.525**	**6.030.903**	83.8
Years of saving over x years				**3.88**		

Calculated at 36 Ft/kWh, the annual savings attainable are HUF 1,100,000 and 16 t of CO2 emissions. The energy saving under actual operating conditions could vary slightly from this prediction.

The measurements show that there could be a 25–35% reduction in the energy consumed by most of the pumps tested. The only major deviation from this was at Váralja sor, where there was a predicted saving of 64%. The results correspond to other measurements carried out in Hungary and other countries. The efficiency of wastewater pumping can be improved by giving preference to the optimum operating condition. Characteristics of the operation of wastewater pumps and pumping stations, such as blockages, treatment plant load demand and wastewater retention time at the pumping station must all be taken into account in the design.

3.3. Applying the results in water supply systems

The results were applied experimentally in Dombóvár Water Works 2 of the utility company Dombóvár és környéke Víz-és Csatornamű Kft.

The wells operated in the water works, the filtration process and the pressure booster pumps were tested. The results found potential savings of between 15 and 55% in the various pumps. Frequency converters with ENQUA*SAVE* (online energy efficiency meter) units and SIEMENS PLC controllers were interconnected into a system by the existing Omron PLC. The basic setting of the system was then performed to attain the operating condition determined by the measurements. After the first three months of pilot operation, the savings attained were as follows:

The average monthly energy saving was measured as 10.849 kWh, or 95% of the saving predicted by the test. (Note: the first three months coincided with the low water consumption period.) Experience gained from the pilot operation was used to adjust the system to harmonize it with changing water demands, satisfy the water quality requirements, and attain further savings.

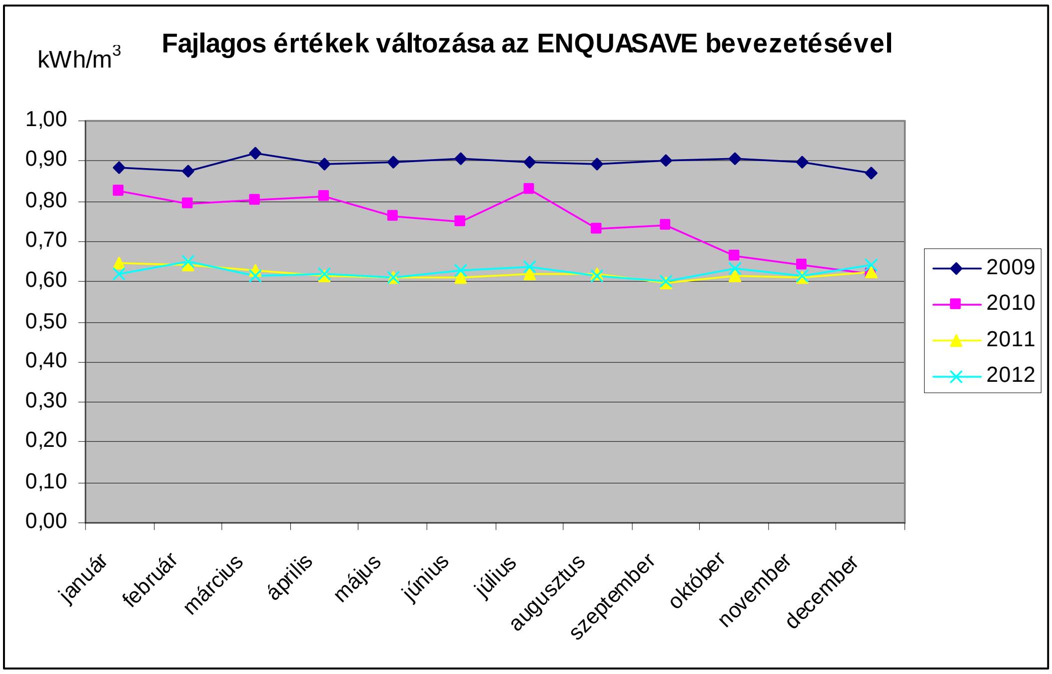
Statistical analysis of actual savings

Monthly savings of 15.000 were attained by the end of the pilot operation, and even higher savings by the end of the year. The higher-than-predicted result derived from the commissioning and integration of three new wells. Their efficiency and energy-efficient operation enabled them to replace some less efficient old wells, such as well 3 at water works site IV. The saving attained at water works site IV operated under the new method of regulation was over 40%, and at site V it was over 25%.

Statistical analysis of unit energy consumption [kWh/m$^{3]}$ of pumps involved in the programme involved pairwise t-test of consumption in the years before and after the change. A change of 5% was considered significant. The average consumption in 2009 was taken as the base condition. Compared with this, energy efficiency improved considerably in the years 2010, 2012 and 2013.

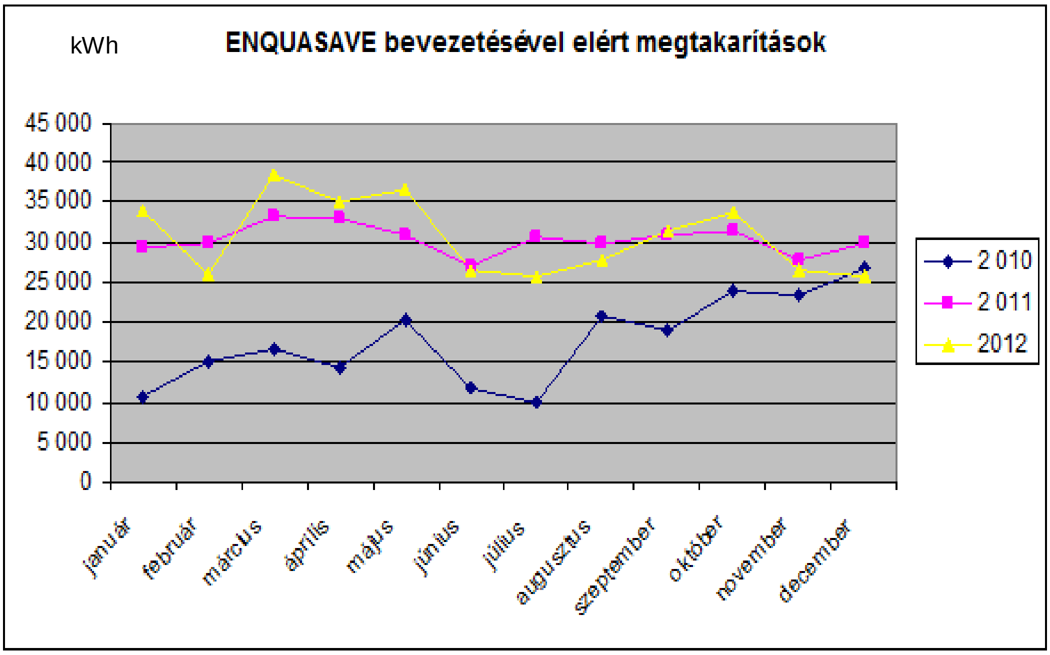
Figure 17 shows how unit energy saving changed following the start of the pilot operation. The decrease in unit energy consumption during operation in 2010 is clear. The figures show the unit values of the average of the two water works sites, the total electricity consumption per unit of water extracted. The site operated with the old settings in 2009. The steady improvement was the outcome of the full system approach. The pumps were optimized as a system as well as individually. The figures for 2011 and 2012 are for the system after full adjustment.

Figure 18 shows the savings achieved. The preliminary predictions were verified in the three years of operation. The monthly savings in 2011 and 2012 regularly exceeded 25.000 kWh, and occasionally 30.000 kWh. The fluctuation of savings was the result of changing water demand and various operational tasks.



[Change in unit values after the adoption of ENQUASAVE]

Figure 17: Unit energy consumption of Dombóvár Water Works in the years 2010–2012



[Savings attained by adoption of ENQUASAVE]

Figure 18: Dombóvár Water Works energy saving in 2010 and 2012

4. CONCLUSIONS AND RECOMMENDATIONS

- I used a new approach in my research, studying the whole process of water transport from wells to reservoirs, and including process pumps and supply pumps. The main objective was to assess and optimize the energy consumption of operating pumps regardless of the pump type. Accordingly, the method may be applied to any pump type and pumping function.
- We carried out test measurements to assess potential savings at three water utility companies in Hungary. The attainable annual savings totalled 740.000 kWh, averaging 21%.
- The experimental application in Dombóvár proved that operation of the pumps in relatively optimum conditions results in considerable savings.
- Attaining energy efficiency requires a change of service strategy. This must involve environmental considerations, a complete change of approach and major IT developments. The outcome could be efficient, energy-saving operation with lower running costs. It could form the basis for reducing consumer charges, in line with government objectives.
- The information given above permits the conclusion that the new measurement method is capable of determining the energy efficiency of pumps to a high level of precision. The measurements form the basis for designing new operational configurations that will yield savings that could pay for developments.

5. NEW SCIENTIFIC RESULTS

- I developed a procedure, based on Danish research findings, to determine with high precision the efficiency of energy consumed in transporting water through measurements conducted on the system in operation, with results expressed in kWh/m^3.
- The test measurement method used in the research provides an accurate means of determining the energy saving potential. The measurements can form the basis for design which delivers savings of energy and CO_2 emissions.
- The pilot application achieved significant savings. The first three years of operation verified the preliminary predictions. The monthly savings in 2011 and 2012 regularly exceeded 25.000 kWh and occasionally 30.000 kWh.
- Analysis of the practical application proved that energy efficiency in water utilities can be enhanced step by step through innovative intervention. Characteristically, the innovative attitude becomes established in this process, by application of various means. The process results in a steady increase in efficiency. The process consists of:
    - designing energy efficiency tests,
    - performing targeted tests,
    - setting up pilot applications at a designated location on the basis of the test results,
    - evaluating the results and involving further locations,
    - optimization in a system,
    - integrating energy efficiency into the water works management system.
- The applied method differs from energy savings attained by replacing the pumps. Its main objective is to assess the energy consumption of operating pumps and optimize their regulation, regardless of the type of pump used. Accordingly, it may be applied to any pump type and pumping function.

6. RESULTS WITH PRACTICAL APPLICABILITY

The measurement results open up the prospect of instituting a practice of operational optimization that could deliver major energy savings. This objective can be attained by proper use of our observations and recommendations. By eliminating certain aspects of operation observed during the study, considerable operating economies may be achieved.

In the case of water extraction wells:

- The wells serving one water works site can differ considerably in their energy efficiency.
- When extraction decreases, the pump is regulated using a gate valve.
- Frequency converters are often used as soft starts.
- The potential of frequency converters is not realized. The are periodically set manually, but not at the optimum point, so that savings are not attained and operating costs rise further.

In the case of pumping stations:

- Owing to decreased water consumption, the installed pumps are too large, and the capacity commitment charge is also too high. Consequently, pump replacement is often the solution of first choice, but gate valve regulation is employed as a temporary measure.

Replacing a pump which is “too big” is a frequent solution to increase energy efficiency. In fact, properly regulated large motors, as the test measurements bear out, are usually more energy efficient than small motors. To cover for extremes of weather, operating a large pump may also be necessary to provide security of supply.

In the case of wastewater pumps:

- Frequency converters are seldom used.
- Even in separate sewers, rainwater can reach the drain, requiring excess capacity. This justifies energetically-regulated operation.

Regulated operation of wastewater pumps provides benefits in addition to energy saving:

- Coordination of wastewater pumps to eliminate adverse effects.
- Evening out the load in the sewage treatment plant.

A great benefit of energy saving developments is that they can be paid for out of the savings themselves. The question arises of when a development may be regarded as economic. Experiences in Denmark show that energy-saving developments that pay back within 8 years are worth implementing. Hungarian operators, however, tend not to embark on developments that pay back in longer periods than 4–5 years. Financing developments could be the greater task, because if the developments do indeed deliver savings, these can provide cover for interest and capital repayments.

7. REFERENCES

Budapesti Műszaki és Gazdaságtudományi Egyetem (2007): Víztisztítás. jegyzet, p.16.

DANFOSS (2006) Kezelés útmutató VLT 5000 sorozat. Danfoss Kft. pp. 65–70.

DANFOSS (2009): Okos megtakarítás az automatizálás terén. DANFOSS DD-SMCC, **www.danfoss.hu** pp. 22–24.

FLEXIM (2008): ADM6725,_manual_hu.pdf www. flexim.com

Gazdasági és Környezeti Minisztérium (2003): Tájékozató az EU kibocsájtás-kereskedelmi rendszeréről és annak magyarországi bevezetéséről, 2003.november

Horváth Z. (2002): Kézikönyv az Európai Unióról. Magyar Országgyűlés, p. 330–337.

http://www.ff3.hu/fejlodes.html

Józsa István (2013): Örvényszivattyúk a gyakorlatban, Invest Marketing Bt. pp. 148–179.

Juhász E. (2008): A csatornázás története. Magyar Viziközmű Szövetség, p. 250.

Karácsony S. – Mészáros G. (1998): Vízellátás – Vízszerzés. Eötvös József Műszaki Főiskola, gyakorlati útmutató. p. 5–10.

Léderer Á. (2010): Az Európai Unió Szerepe a Klímakonferenciákon. BGF Külkereskedelmi Kar, jegyzet.p.22.

KSH (2014): Magyarország közigazgatási helynévkönyve. www.ksh.hu

MAVIZ – Műszaki Bizottság (2010): Szivattyúk energetikai vizsgálata-a szivattyúzás általános áttekintése a viziközmű szolgáltatásban. 2–49.

Steffensen, P. (2011): Vesthimmerland Forsyning Stistrup Rensenanlaeg, mellenpumper, Foranalyse. p.5 www.picca.dk

8. PUBLICATIONS OF THE SUBJECT OF PhD

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Registry number: DEENK/128/2015.PL
Subject: Ph.D. List of Publications

Candidate: Ferenc Zsabokorszky
Neptun ID: PNWLE0
Doctoral School: Kerpely Kálmán Doctoral School of Corp Production, Horticulture and Regional Sciences

List of publications related to the dissertation

Hungarian scientific article(s) in Hungarian journal(s) (7)

1. **Zsabokorszky F.**: Az Európai Uniós csatlakozásunk hatása a szennyvíztisztításra.
   Magy. Ip. Környvéd. Mag. 13 (1-2), 17-19, 2014. ISSN: 1588-3809.

2. **Zsabokorszky F.**: Rezsicsökkentés a viziközmű szolgáltatóknak is.
   Magy. Ip. Környvéd. Mag. 12 (1-2), 14-15, 2013. ISSN: 1588-3809.

3. **Zsabokorszky F.**, Spindelberger W.: Szennyvíziszap-hasznosítás Ausztriában.
   Vízmű Panor. 21 (4), 22-23, 2013. ISSN: 1217-7032.

4. **Zsabokorszky F.**: Új energiamagtakarítási innováció a szivattyúzásnál.
   Magy. Ip. Környvéd. Mag. 10 (1-2), 24-25, 2011. ISSN: 1588-3809.

5. **Zsabokorszky F.**, Steffensen P.: Energia optimalizálás vízművek szivattyúinál.
   Környezetvédelem. 17 (6), 28, 2009. ISSN: 1216-8610.

6. **Zsabokorszky F.**: Mi történik a szennyvíziszappal az Európai Unióban.
   Környezetvédelem. 16 (5), 7, 2008. ISSN: 1216-8610.

7. **Zsabokorszky F.**, Nagy G.: Mobil szennyvíziszap víztelenítési technológiák alkalmazhatósága a nemzeti szennyvízprogram tükrében.
   Vízell. Csatornázás. 7, 58-60, 2004. ISSN: 1585-5260.

Foreign language scientific article(s) in international journal(s) (2)

8. Ligetvári, F., **Zsabokorszky, F.**, Kovács, K., Zsirai, I.: Wastewater Treatment and Sludge Utilisation in Hungary.
   J. Env. Sc. Eng. 4 (3), 141-147, 2015. ISSN: 1934-8932.
   DOI: http://dx.doi.org/10.17265/2162-5263/2015.03.005

9. **Zsabokorszky, F.**: Socio-Political Reception of Sewage Sludge Recycling:The Hungarian Perspective.
   J. Res. Sci. Tech. 8 (4), 159-164, 2011. ISSN: 1544-8053.
   IF:0.508

Hungarian conference proceeding(s) (1)

10. Ligetvári F., **Zsabokorszky F.**: Szennyvíztisztítás és iszaphasznosítás.
    In: Víz és szennyvízkezelés az iparban [elektronikus dokumentum]. Szerk.: Rodek Nóra, Soós Ernő Víztechnológiai Kutatóközpont, Nagykanizsa, [6], 2014. ISBN: 9789633960394

Foreign language conference proceeding(s) (2)

11. **Zsabokorszky, F.**: A future challenge for environmental management: Raising energy efficiency in the water utilities sector.
    In: 4th International Joint Conference on Environmental and Light Industry Technologies [elektronikus dokumentum]. Ed.: Ákos Borbély, Óbuda Univ., Budapest, 98-100, [2014].
    ISBN: 9786155018930

12. **Zsabokorszky, F.**: Present and Future Sewage Sludge Treatment in Hungary and its Energetic Utilisation.
    In: 3rd ICEEE International Scientific Conference on Environmental Engineering [elektronikus dokumentum]. Ed.: Hosam Bayoumi Hamuda, Óbuda University, Budapest, 245-253, 2012.

Total IF of journals (all publications): 0,508
Total IF of journals (publications related to the dissertation): 0,508

The Candidate's publication data submitted to the iDEa Tudóstér have been validated by DEENK on the basis of Web of Science, Scopus and Journal Citation Report (Impact Factor) databases.

16 June, 2015