Evaluation methods for comparing energy savings due to variable speed pumping in wastewater applications

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LIU-IEI-TEK-A—14/01817—SE
Abstract

The Master Thesis work has been carried out at Xylem HQ, Sundbyberg, Sweden in collaboration with Linköping University, Department of Management and Engineering. The work was to evaluate in different ways energy savings in wastewater pumping stations and conclude what is the discrepancy between them, emphasizing on the theoretical model and measured data.

Two pump stations were chosen to be modeled by mathematical calculations based on theoretical pump and system curves. Based on the same inputs, a commercial tool was used to calculate energy savings. Moreover, theoretical curves and variable speed drives were combined into an own developed testing platform in LabView, as an alternative evaluation solution. Finally, measured data was collected and used in a specific energy algorithm, designed to have as inputs water level and energy.

In term of method accuracy, initial assumptions are wrong. For a given frequency, the results show similar values for all four evaluation methods. Also, variable speed is confirmed as a good control philosophy for less energy use than direct online.

**Key words: Pumping, energy, control methods, E₁₆ algorithm.**
Acknowledgement

First of all, I would like to thank my beloved family for their extraordinary support and help. I also want to thank Xylem Water Solutions for funding my research and providing me all the necessary information to reach my aim. I am grateful to my supervisor at Xylem Water Solutions, Jürgen Mökander, and the personnel from the R&D Department, who during my thesis work helped me by providing ideas and technical solutions in order to achieve the goals we fixed at the beginning.

I would also like to give special thanks to Cyril Gueret and Alexander Fullemann at Xylem Water Solutions, who provided me valuable feedback, field and laboratory support.

I also take this as an opportunity to thank Linköping University and its employees. I am grateful to my examiner, Patrik Thollander, and to my supervisor, Mats Söderström, for his unconditioned help.
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DOL – direct online
BES – Best efficiency speed
BEP – Best efficiency point
VS – variable speed
VFD – variable frequency driver
HIL – Hardware In the Loop
STR - System Test Rig
1. Introduction

The main reason for conducting this study is that nearly 20% of the world’s electricity is used by pumping systems and is ranging from 25 – 50% of the electricity needed in some industrial plant operations. Pumping systems are a widespread throughout the world and are used in agriculture, by municipalities or industries. Even though pumps are purchased as individual components, the only way they can operate is within a system [1].

An important aspect associated with pump stations, i.e. facilities where pumps are running, is the cost. The use and maintenance phase represent more than 90% of the total lifetime cost. In theory, an intelligent control method should have the possibility to decrease the amount of used energy and the number of maintenances.

1.1. Objective and Aim

The main objective of this project work is to evaluate pump control methods with different available tools: theoretical calculation, simplified theoretical model, graphical simulation, and measured data from real pump stations. The two control philosophies taken into consideration are ON/OFF control and variable speed. By having the above mentioned results, the report aims to identify what the difference between those evaluation tools is.

The objective has been divided into two research questions (RQ) which are formulated below:

RQ1. - How big is the difference between results when using different evaluation methods?
RQ2. - Is the use of a variable speed control method an efficient way to minimize the energy use of a pump station during its lifetime?

1.2. Limitations

The project work includes several limitations that are mentioned below. The focus of the report is on the use and maintenance phases of wastewater pump stations, because these parts have the biggest impact in the whole lifecycle.
The purpose of the thesis work is to verify the difference in accuracy between the evaluation methods, so the number of pump stations is not a relevant factor in our equation. The study is limited to a number of two facilities (laboratory and one municipal pump station). The chosen municipal pump station needs to be close to Xylem headquarters, so that it can be visited several times, for data recording and verification of the instrumentation.

Other limitations are related to time and the interference of other test that are done in the two pump stations. Measured data should be logged for both control methods with the same start and running conditions during similar periods of time.
2. Background

The aim of the chapter is to give a brief introduction and explain what the distinct research fields involved in the project are. The first part gives a short presentation of Xylem Inc. The second part explains about the environment where pumps are running.

2.1. Xylem

Xylem has around 12000 employees in more than 150 countries and a lot of resources to find innovative solutions for the world's water supply. They produce and sell pump systems, controllers, water and wastewater treatment systems and analytical instruments [3].

Their main purpose is to help people use water in a more effective way in households, industry, and farms. A major part of their work is to develop new technologies that can improve the way people use, store and reuse water [3]. Apart from this, they are also working actively to raise awareness among others about the importance of preserving and protecting the world's water resources. A good example is the Stockholm Water Prize [3].

2.2. Pump station

As can be seen in figure 1, a pump station is a structure that houses pumps, pipes, valves, and auxiliary equipment. Usually, it includes two or more pumps, an inlet and an outlet and often a check valve, which prevents the water to go back into the sump. Usually, only one pump runs, while the other/s are in standby. An alternation process is implemented, i.e. during a period of time pumps will all run the same number of times, so that the pumps will wear evenly. During periods of high inflow more than one pump will run.

There are three main types of pumping stations: water pumping stations, wastewater pumping stations, and sludge pumping stations. Based on the application’s requirements, there are different types of sumps: unconfined, rectangular, trench-type, circular, can, submerged barrel intake, confined, formed suction intake for large stations, manifold and suction tank [5].
A very crucial key for increasing the lifetime of a pump is a proper design of the sump. Pumps should be provided for optimal inlet conditions. This means that the inflow should be uniform, steady and without entrained air or swirl. Basic design recommendations for achieving hydraulic requirements, energy efficiency and reliability are that [6]:

- Flow should be directed to the inlet of the pump
- Stagnation or low flow regions should be avoided
- Adequate clearance should be provided between the pumps and from the sump walls and floor
- Adequate submergence should be assured
- Protection against air entrainment and swirl
- Avoid sedimentation by having a sloped floor
- Cleaning cycles necessary for wastewater to prevent clogging
3. Pumps and pumping systems

This chapter describes characteristics and performance of pumps and pumping systems, along with the methods of evaluating energy savings.

3.1. Pump

A pump is a device or machine which is designed to increase the energy level of a liquid. It is usually used for pumping fluid from one place to another. The term pump is applied to the machine itself (limits set by terminal points: inlet and outlet connections, drive shaft, connections to seals). There are pumps with integrated motors and it can also have terminal points [7].

Pumps are divided into two different technologies according to their working principles: kinetic and positive displacement. Kinetic pumps can be centrifugal (most common) or propeller pumps. Positive displacement pumps are separated in reciprocating pumps, rotary pumps and pneumatic pumps [5].

The pumps that Xylem usually uses are submersible wastewater centrifugal pumps. As seen in figure 2, in contrast to classical pumps, submersible pumps have a compact unit where the pump is united with the motor and it is located on a single short shaft. Because of this, energy transmission from the motor to the impeller is made with minimum loss. Vibration, noise, and effects on the bearings and on the mechanical seals are also minimized. Submersible pumps have high flow capacity relative to their size and they are structurally simple and robust [4].

Figure 2: Xylem wastewater pump (published with kind permission from Xylem) [21]
Modern demands for wastewater pumping stations are very well met by submersible pumps. These demands are [4]:

- Reliability and continuity of service (including cases of emergency)
- Minimizing or even removing the need for operating personnel
- Eliminating emergency output
- Minimizing the noise
- Preventing unauthorized users
- Adaptability in case of variable flow
- High energy efficiency

A good example of using submersible pumps is the city of Stockholm where all 350 wastewater pumping stations are equipped with this type of pumps. The service or the routine check-up is made by four relief teams [4].

3.2. Pump control methods

Pump control means control of a pump in a pump station and it is almost completely done automatically. It is responsible for executing several functions, for example running pumps to handle the inflow, managing alternation between pumps, pump and pipe cleanings, managing alarms, etc. The level in the sump is controlled with the help of level sensors and float switches. This gives the pump a start and stop interval. There are two types of control that are being used in pumping applications:

- **ON/OFF (DOL)**
- **Variable speed (VS):**
  - Constant Level Control
  - Best Efficiency Speed (BES)

**DOL** control means that every time water reaches start level, the pump starts with the frequency of grid (50 Hz or 60 Hz) and keeps it unchanged until it reaches the stop level. As it is shown in figure 3, for this method the inflow ($Q_{in}$) is not equal to the outflow ($Q_{out}$).
Constant level control means that the level in the sump is kept constant, so the outflow ($Q_{out}$) has the same value as the inflow ($Q_{in}$), as it is shown in figure 4.

Best efficiency speed means that the controller is running the pump at the speed where it uses the minimum amount of energy to move a certain amount of water. As in DOL control, the inflow ($Q_{in}$) is not the same as the outflow ($Q_{out}$); it is the sum between the inflow and the pump flow.
The difference between DOL and VS makes the choice of one of them to have major consequences, so before this is done, a detailed analysis of the system should be performed. When a system has a high percentage of friction losses relative to the total head, the most suitable solution is the VS control. On the other hand, more pure lift systems do not need this method, so DOL is the recommended control solution [12].

There are two ways of achieving variable speed (VS). The first option is mechanically, through a set of gears and the second one is electrically, with the help of a VFD. There are many companies that manufacture and use VFDs.

Advantages of VS pumping compared with DOL [5]:

- Better management when having a variable flow
- No storage required, so the sump can be smaller, shallower and less expensive than for DOL (it compensates for the high cost of the VFD)
- More space is saved in the sump by using less pumps and equipment
- Reduces the production of corrosive gases and odors
- Energy use is lower, pumping rates are lower, pipe friction losses are lower
- Motor life is expanded (infrequent start)
- “Soft” starts
- Voltage dips are reduced

Disadvantages of VS pumping compared with DOL [5]:

- Adds significant cost and complexity
- Requires more equipment and maintenance, reduced reliability
- Troubleshooting and repair requires specialized personnel
- More difficult to avoid vibration (needs a good design) and noise
- Instrumentation is more costly (because higher accuracy is needed)
- Not efficient for flat systems, where there are not that many friction losses.
3.3. Pump principles and performance characteristics

This subchapter describes what the followed principles are in order to select a pump for a specific application.

3.3.1. Pump performance curve

As it can be seen in figure 5, the pump performance curve is a graphical description of the pump’s characteristic. It shows the relationship between flow rate (Q) and head (H) for a specific pump [19].

One parameter that can influence the position of the curves by moving them upward (increase head and flow) is increasing the impeller diameter. The other is raising the speed. Also, by connecting two or more pumps in series, the head’s capacity will increase. If they are connected in parallel, the flow’s capacity will increase [19].
3.3.2. System curve

When considering a system of pipes, it can be stated that the system curve is a graphical representation of the relationship between pump discharge and head losses (dynamic head), as seen in figure 6. It is totally independent of the pump characteristics [20].

The head of the system is a function dependent on the elevation, which is the difference in meters between the pump stop level and the beginning of the pipe system [19]:

\[ H_T = H_S + H_L \]  
(Eq.1)

Where:
- \( H_T \) is the total head [m]
- \( H_S \) is the difference between the inlet and the outlet (also called static head) [m]
- \( H_L \) are the system losses (also called system head) [m]

The static head is independent of the piping system. The system losses follow the expression [19]:

\[ H_L = k \times Q^2 \]  
(Eq.2)
Where:

\( k \) is a constant that describes the total system characteristics

\( Q \) is the flow \([\text{l/s}]\)

### 3.3.3. Operation point

As seen in figure 7, the intersection between the actual pump curve and the system curve is called operation point or duty point [19].

![Figure 7: Duty point (Operation point)](image)

The best efficiency point (BEP) is the duty point for the best operation conditions, where the maximum efficiency of the pump is found [19].

### 3.3.4. Power and efficiency of a pump

As can be seen in figure 8, the power associated with pumps regards the following [19]:

11
- Input power is the electrical power used at pump junction box (connection to electricity grid):

\[ P_i = 3^{1/2} \times U \times I \times \cos \phi \]  
(Eq.3)

Where:

- \( P_i \) is input power [W]
- \( U \) is the voltage [V]
- \( I \) is the electric current [A]
- \( \cos \phi \) is the power factor

- Shaft power is the power used at the end of the shaft:

\[ P_S = T \times \omega \]  
(Eq.4)

Where:

- \( P_S \) is shaft power [W]
- \( T \) is the torque [Nm]
- \( \omega \) is the rotational speed [rad/s]

- Hydraulic power is the power transmitted to the water:

\[ P_H = Q \times H \times \rho \times g \]  
(Eq.5)

Where:

- \( P_H \) is hydraulic power [W]
- \( Q \) is the flow \([\text{m}^3/\text{s}]\)
- \( H \) is the head [Pa]
- \( \rho \) is the fluid density [kg/m\(^3\)]
- \( g \) is the gravity [9.81 m/s\(^2\)]

Pump total efficiency is the ratio between hydraulic power and input power [19]:

\[ \eta = \frac{P_H}{P_i} \]  
(Eq.6)
Where:

\[ P_i \text{ is the input power [W]} \]

\[ \eta \text{ is the efficiency} \]

Figure 8: Energy flow in pumps (published with kind permission from Xylem) [21]

### 3.4. Specific energy

This subchapter describes the core logical expression that calculations are based on and the four existing methods of computing the results. By comparing the two different control methods in terms of energy usage it can be seen which one is the most suitable solution, i.e. the one that uses the least amount of energy. If in theory it is easy to calculate (a mathematical model based on pump and VFDs efficiency, power, a constant volume, etc.), in reality things are different because the pump station inflow is always variable.

By knowing which type the system is, a suitable control method can be suggested. In some cases, the VS method can use less energy, in others the DOL method can. There are a lot of factors that influence the use of energy: system specification, inflow (raining season, melting of snow,
overflowing), mechanical or electrical problems etc. So, there is a need of a dependency between the pumped volume of water and the energy used to realize this process.

That is why in pumping applications energy cannot be the only one used to compare control methods and instead of that the formula for specific energy is used:

\[ E_{sp} = \frac{E}{V} \]  

(Eq.7)

Where:
- \( E \) is the amount of energy used during a chosen period of time \([\text{kWh}]\)
- \( V \) is the pumped volume of water \([\text{m}^3]\)
- \( E_{sp} \) is the specific energy for a specific pumping system \([\text{kWh}/\text{m}^3]\)

Furthermore:

\[ E = P_i \times t \]  

(Eq.8)

Where:
- \( P_i \) is the input power \([\text{kW}]\)
- \( t \) is the time \([\text{h}]\)
- \( E \) is the energy \([\text{kWh}]\)

For the volume calculation two formulas are used:

Formula used in measurements:

\[ V = A \times \Delta h \]  

(Eq.9)

Where:
- \( A \) is area \([\text{m}^2]\)
- \( \Delta h \) is the difference between height samples \([\text{m}]\)
- \( V \) is the volume \([\text{m}^3]\)

The above formula was chosen for calculating the volume in real applications because of an easier way to collect data from any level measurement device in comparison with flow measurement, which is a very sensitive method and has a lot of uncertainties.

Formula used in theoretical calculation:

\[ V = Q \times t \]  

(Eq.10)

Where:
- \( Q \) is inflow \([\text{m}^3/\text{s}]\)
The above formula was chosen for theoretical calculation, because by having the pump and system curve, the flow for the duty point can be computed and then the total volume can be calculated.

There are different tools available for evaluating specific energy, like theoretical calculation, measured data, and some combinations between the first two. Each of them has advantages and disadvantages which will be stated later on. Figure 9 shows a preliminary assumption on the accuracy of the evaluation methods, in comparison with measured data. It can be seen that measured data is supposed to be the most difficult to use from the evaluation methods, but with the highest accuracy, while the simplified model adds a lot of assumptions that makes it less accurate, but easy to use.

![Figure 9: Methods for evaluating specific energy – initial estimation](image-url)
4. Methods

This chapter describes various strategies and processes that are involved in completing the project work. The first two parts are comprised of the main steps included in the research process and a short analysis of the accuracy of the collected data. They are followed by the methods used during the sensitivity analysis and the specific energy calculation steps.

4.1. Research process

As seen in figure 10, the research process presents in a detailed way the procedures adopted in executing this project work.

Figure 10: Research process
A literature review has been carried out to further broaden my knowledge area on the concepts of the research fields and apply them in my report (pumping control methods, different ways of calculating energy usage etc.). During this step, the information was acquired from personal communication, Xylem’s library, and also from the web.

Several articles and books, which were referenced throughout the report, present the advantages of using VFDs and the amount of savings made with their help, but none put in perspective the difference between different methods of calculating specific energy and their accuracy.

One meeting with a reference group was organized to offer support and guidance. Each member has a different background experience: Johanna Johansson (LCC), Mats Karlen (Hydraulics), Cathrin Stock (LCA), Gunnar Sandell (Monitoring & Control), Cyril Gueret (Energy Audit), Jürgen Mökander, Alexander Fullemann, Henrik Myringer and Martin Zetterquist (Electrical).

After identifying which control methods are used in pumping applications and evaluating their strengths and weaknesses, the different methods of calculating energy use are described. By identifying and defining the specific system, three scenarios have been developed to compare the above mentioned control methods from an energy point of view.

The data is compiled and the results are presented in the report in a comparative way by using examples of pump stations where there is full control and where inputs are reliable.

4.2. Data analysis

The study requires numerous data, which is used throughout the report. Dedicated data collection has been performed for this study. Each methodology of calculating the specific energy needs precise inputs (pump curves, system curves, power and efficiency curves, etc.). Some of the input data is collected from instrumentation (water level and energy), which has also uncertainties because of logging time, tolerances of the measuring devices and internal calculations.

Reliable data about pump stations and inside instrumentation are mainly gathered from Xylem’s technical specification documents. When talking about the algorithm’s robustness, it needs to be specified that the devices from the sump (pumps, mixers, level sensors, cables, etc.) and the piping system are not taken into consideration when calculating the volume.
4.3. Method of conducting the sensitivity analysis of the algorithm

This subchapter describes the steps and the way the sensitivity analysis was conducted. Firstly, for generating the simulated events tested in the algorithm, information about real pump stations was reviewed and key elements that have the biggest impact on their behavior were identified.

As it can be seen in the attachments, an event simulator named “Test Generation” was created in Excel. It handles different cases that are required to test key parameters. It is a flexible tool because of the possibility to modify the value of several elements such as the sump area, start and stop levels, constant inflow, outflow, variation period and limits for variable inflow. Water level logging can be simulated every second or every 60 seconds. Pump outflow can be simulated in two ways: constant pump flow or pump flow that is linearly dependent on the head. For the inflow, there is the option of constant inflow and variable inflow. Because of the importance of volume calculation from a sensitivity point of view, more focus was on that part.

4.3.1. Collection of the input data

For providing the results, there are two parameters that are used as inputs by the algorithm: water level and energy. They are both collected via a logging device, i.e. Netbiter EC220 [22]. Figure 11 presents the process of logging and saving data.

![Diagram](image)

Figure 11: Netbiter EC220
Netbiter is a plug-and-play device, simple and easy to install, configure and maintain. Regarding the way data is logged, they state that, during every chosen period of time (60 seconds/5 minutes/60 minutes), the device takes one sample and records it. It is connected to a web server, where all the logged data is securely stored [22].

Netbiter is set to log level data every 60 seconds and energy data every 60 minutes. The difference between saving samples for level and energy is due to the time it takes for a sample to change its value. Several problems can happen during this period of time. A device malfunction can cause a disruption in results. Another issue is that Netbiter takes data from VFDs, which can also be susceptible to flaws (power failure, loss of connection etc.).

Another aspect than can pose problems to the calculation is the level sensor position. In general, the geometry of a sump is similar to the one shown in figure 12. Movement of the level sensor (stretching or rupture of the cable) can be caused by different factors and has a major influence on the precision of the algorithm, because the logged values of the water level are wrong and also the area of the sump can vary.

![Figure 12: Sump geometry](image)

4.3.2. Analysis of the parameters

For this part of the sensitivity analysis it is assumed that the saved input data is logged in a proper way. A simple example based on data provided from known pump stations is used to compare the
output of the algorithm with the theoretical results. It assumes that there is a pump station with two pumps and a logging device that saves one level sample every $x$ seconds and one energy sample every $y$ minutes. The measurements take place during one day. Pumps have a start level of $h_1$ m and a stop level of $h_2$ m. When the simulation starts, the water level is the same as the stop level.

Volume calculation:

$$V = A \times (\text{start level} - \text{stop level})$$  \hspace{1cm} (Eq.11)

Several parameters are taken into consideration in the sensitivity analysis: logging time (60 seconds vs. 1 second), constant inflow vs. variable inflow, constant pump outflow vs. pump outflow linearly dependent on the head, as seen in figure 13.

![Figure 13: Linear function for pump outflow](image)

$$q_n = a + b \times h_n$$  \hspace{1cm} (Eq.12)

Where:
- $a$, $b$ are known
- $h_1$, $h_2$ are stop and start levels
- $q_1$, $q_2$ are minimum outflow and maximum outflow
The energy calculation part of the algorithm is not affected by any of the parameters, so it will not be taken into consideration in this part of the analysis. There is no significant variation within less than one hour.

By isolating the parameters mentioned above one by one, several scenarios were developed to show what the impact of each is:

1) **Logging time (60 seconds vs. 1 second)**

Usually, the logging time between each value of water level is 60 seconds. As seen in the steps of the $E_{in}$ algorithm, for computing an average that will replace the negative part there is need of at least three values (180 seconds) before and after the pumping cycle, which also needs to contain a minimum of three samples, so that the filtering part will not affect the calculations. The accuracy of the results is related to the number of samples that each cycle has. Thus, by logging every second, more samples will be provided for a more appropriate value to the theoretical one.

To see what the effect of the logging time on the volume calculation part of the algorithm is, there is need to minimize the influence of other parameters, i.e. it is assumed that both the inflow and the pump outflow are constant.

**Scenarios:**
As mentioned above, logging data takes place every 60 seconds and each cycle needs at least three samples. It is needed to compare the algorithm’s output when data is logged every 60 seconds with the one when saving data every one second, with the same settings for inflow and pump outflow, to show possible modifications in result. In addition, each cycle can be short (less than 180 seconds) or long (more than 180 seconds).

2) **Constant inflow vs. variable inflow**

In real time applications the inflow is rarely, almost never constant, so there is a need to check the algorithm’s behavior when a variable inflow is used as input. To see what the effect of the inflow on the volume calculation part of the algorithm is, the influence of other parameters needs to be minimized, i.e. assumptions are that logging time is one second and the pump outflow is constant. Also, the definition of cycle time is introduced, i.e. the speed of a 2-way running cycle (water level rise + pumping cycle).
Scenarios:
In these scenarios, the influence of variable inflow is tested by varying the period of time the inflow varies or the interval between occurrences.

3) Constant pump outflow vs. pump outflow linearly dependent on the head

As in the case of the inflow, pump outflow is never constant in real time applications. A more realistic way to simulate the pump’s behavior is to use a linear approximation of the outflow based on the head (geodetic height). To see what the effect of the pump outflow on the volume calculation part of the algorithm is, it is assumed that logging time is one second and inflow is constant.

Scenarios:
In these scenarios, the effect of a constant pump outflow is compared to a linearly dependent one to the head.

4) Combination between parameters

If in the above cases, parameters were isolated, so that the errors would reflect only specific changes, in this part a combination between them shows how a real-time application would behave.

Scenarios:
In these scenarios, examples where water level is recorded every 60 seconds, inflow is variable and pump outflow is linearly dependent on the head are given.

4.4. Methods of calculating specific energy

The four methods of calculating specific energy (theoretical, simplified, HIL and data measuring) were applied on two real cases (in laboratory environment and in a municipal pump station) for two control methods (DOL and BES).
4.4.1. Theoretical calculation

The mathematical calculation of the $E_{sp}$ is mainly based on the theoretical pump and system curves, as seen in figures 5 and 6.

Steps in calculation:

1) Collect values for creating pump, power and efficiency curves at 50 Hz from the pump manufacturer

2) Collect values for creating system curves from the sump designer

3) Compute the values for creating reduced pump curves (same $Q$, different $H$) with the information regarding piping system, as seen in figures 14 and 15.

Figure 14: Reduced pump curve

\[ H_r = H - \left( H_S + \frac{H_L}{Q_p^2} \times Q^2 \right) \]  \hspace{1cm} (Eq.13)

Where:

$H_r$ represents the reduced head [m]

$H$ represents any of the head values from the pump curves [m]

$H_S$ is the static head [m]
\( H_L \) represents the friction losses in the system [m] at a given flow \( Q_p \) [l/s]

\( Q \) is any of the flow values from the pump curves [l/s]

Furthermore:

\[
H_L = H_T - H_S \quad \text{(Eq.14)}
\]

Where:

- \( H_L \) represents the friction losses [m]
- \( H_T \) is the total head [m]
- \( H_S \) is the static head [m]

4) Based on the reduced pump curves and power curves at 50 Hz, compute the equivalents for lower frequencies (for one pump); use affinity laws [23]:

\[
\frac{Q_1}{Q_2} = \left( \frac{n_1}{n_2} \right) \quad \text{(Eq.15)}
\]

\[
\frac{H_1}{H_2} = \left( \frac{n_1}{n_2} \right)^2 \quad \text{(Eq.16)}
\]

\[
\frac{P_1}{P_2} = \left( \frac{n_1}{n_2} \right)^3 \quad \text{(Eq.17)}
\]

\[
\frac{\eta_1}{\eta_2} = 1 \quad \text{(Eq.18)}
\]
Where:

\[ n_1, n_2 \text{ are shaft rotational speed [Hz]} \]

\[ Q_1, Q_2 \text{ are flows [l/s]} \]

\[ H_1, H_2 \text{ are heads [m]} \]

\[ P_1, P_2 \text{ are powers [kW]} \]

\[ \eta_1, \eta_2 \text{ are efficiencies} \]

5) Because the two pumps are in parallel, the system has the same head; only the flow and the power double their value.

6) Based on the pump and system curves, calculate the flow and head of the duty point for all frequencies (curve intersection), as seen in figure 7.

7) Because the values of the flow are very close one to another, the total efficiency can be calculated as a point on a line between two consecutive flows with the linear equation, as seen in figure 16:

\[ y = m \times x + n \]  \hspace{1cm} \text{(Eq.19)}

Where:

\[ m, n \text{ are designated constants} \]

\[ x, y \text{ are coordinates} \]

[Figure 16: Efficiency calculation]
8) Based on duty flow, head and efficiency, calculate the input power:

Without VFD:

\[ P_i = \frac{\rho \cdot g \cdot Q \cdot H}{\eta_m \cdot \eta_p} \]  
(Eq.20)

With VFD:

\[ P_i = \frac{\rho \cdot g \cdot Q \cdot H}{\eta_p \cdot \eta_m \cdot \eta_{VFD}} \]  
(Eq.21)

Where:

- \( P_i \) represents the input power [kW]
- \( Q \) is the duty flow [l/s]
- \( H \) is the duty head [Pa]
- \( \rho \) is the density of the liquid [kg/m\(^3\)]
- \( g \) is the gravitational constant [m/s\(^2\)]
- \( \eta_p \) is the efficiency of the pump
- \( \eta_m \) is the efficiency of the motor
- \( \eta_{VFD} \) is the efficiency of the variable frequency drive

9) Calculate \( E_{sp} \) for each frequency:

\[ E_{sp} = \frac{P_i}{Q} \]  
(Eq.22)

Where:

- \( E_{sp} \) represents the specific energy [kWh/m\(^3\)]
- \( P_i \) represents the input power [kW]
- \( t \) is the time [s]
- \( Q \) is the duty flow [m\(^3\)/s]

10) For any chosen inflow, calculate \( E_{sp} \) during one period of time with 50 Hz and with the frequency that has the smallest \( E_{sp} \).

11) Compare \( E_{sp} \) for both the cases and see what is the difference between them in percentage.

Some advantages related to the theoretical model are that it gives a more accurate result of the specific energy and with the help of the duration diagram, different inflow cases can be simulated.
The weak points are that a large amount of data is needed for input and that data can be wrong; there are also tolerances integrated into the values.

For the theoretical calculation, all the necessary information was taken from Xylect [32], which is a pump selection tool used by Xylem, and the system description datasheet. The steps mentioned above are followed. Specific energy is calculated every one Hz from 50 Hz to 30Hz. The value corresponding to the optimal speed and the one corresponding to 50 Hz are saved.

4.4.2. Simplified theoretical model

This is a commercial software used by Xylem that is based on a simplified theoretical model. The role of this model is to compare DOL with VFD control for a regulated pump station with two pumps, one duty and one standby. It is used as a fast and easy, but not so accurate, calculation method.

Description of major components and their role in calculation, as seen in figure 17:

![Energy calculator GUI](published with kind permission from Xylem) [13]
1) **Rated power of a pump** [kW]: used to roughly calculate the input power (assumed to be 90% of the rated power)

\[ P_i = 90\% \times P \text{ [kW]} \]  
(Eq.23)

2) **Static head/total head**: used to approximate the difference in percentage between the total head and the friction losses

   a. Total head represents the sum between the static head and the friction losses, as seen in figure 6

3) **Pumped media**: used to select the type of media where the pumps are installed (options: Clean water, Fine screened sewage or Raw unscreened sewage)

4) **Impeller type**: used to select the type of impeller the pump has (options: Open single vane, Closed single vane, Closed two vane, N-technology, Screw or Vortex)

   a. In each type of media a pump has a specific efficiency, which is based on the impeller type.

   - **Media X**:  
     - **Impeller A**: \( \eta_1 \) [%]  
     - **Impeller B**: \( \eta_2 \) [%]

   b. All efficiency values are averages based on company experience and values measured in different pump stations all around the world.

5) **Motor efficiency class**: used to select one of the efficiency classes (options: Standard efficiency \(<\text{IE1}>\), High efficiency \(<\text{IE2}>\) or Premium efficiency \(<\text{IE3}>\))

   a. Based on the rated power of the pump, for each class, a different efficiency of the motor exists.

   - **Rated power**:  
     - **Standard efficiency**: \( \eta_3 \) [%]  
     - **High efficiency**: \( \eta_4 \) [%]  
     - **Premium efficiency**: \( \eta_5 \) [%]

6) **VFD controller**: adds two VFD controllers to the system

   a. Assumptions:

   - Pumps are dimensioned for peak flow.
   - VFD controller will reduce the friction loss by an average of 75%.

\[ 100 - (H_S + H_L/4) = x \text{ [%]} \]  
(Eq.24)

   Energy savings are reduced by 10% due to sump and pipe cleaning functions.

   - \( x \times 0.9 \) [%]
   - VFD increases the energy use with 4%.

   - \( x \times 0.96 \) [%]

   Reduced motor efficiency as it operates partly loaded.
This tool's advantages are the easy way of calculating the energy savings potential, the fact that it does not need too much input data (Rated power, Operation time, Static head/total head, Pump media, Impeller type, Motor efficiency class), it is accessible to all persons that go on Xylem’s site and it is a fast solution for a rough comparison between DOL and VFD control method.

Its disadvantages are that it includes multiple assumptions in calculation steps and it only covers certain applications (assumes that both pumps are of the same type, assumes that the pump station has only two pumps, etc.)

The same sources of information as in the theoretical model and the steps from above were used for the simplified model. This has a user-friendly interface and gives as an output a percentage of how much energy you can save if you use a VFD in comparison with DOL.

### 4.4.3. Hardware in the Loop (HIL)

It is an own developed simulation tool. It was created in LabView as a platform for testing pump controllers, as seen in figure 18. It is used as a graphical representation of theoretical calculations.

![Figure 18: HIL connection schematics](image-url)
The LabView program is divided in two parts:

1) **Main**, used to set up/load the testing conditions, as seen in figure 19:
   Possibilities of use:
   a. Manual (Manipulate parameters that are found in the right side tabs and press “Run” or press “Load system” and then “Run”).
   b. Excel input (Configure or “Load system”, choose test sequence, press “Load Test Sequence” and then “Run”).

2) **Simulation**, used to visualize and manipulate events/actions created in **Main**, as seen in figure 20:
   Possibilities of use:
   a. Manual (Press “Start” to run the program, then “Stop” to end it and “Close” to close it and return to “Main”).
   b. Excel input (Press “Start” to run the program; when the last event passes, “Stop” is automatically pressed and an output Excel file appears; press “Close” to close it and return to “Main”).

![Figure 19: Main GUI](image-url)
The program offers as an output a graphical representation of the water level, duty point, which pumps and corresponding VFDs run etc. it calculates values of specific energy, outflow, pumped flow, input power, energy losses, number of pump starts, flow, head etc.

Its strong points are that it is mainly based on the theoretical curves (pump and system curves) and formulas, it is a very flexible tool (can input sump design parameters and piping system, constant/variable inflow, different actions etc.) and that it can control and log large amount of data. It keeps the same starting and operating conditions throughout the whole testing period.

An important disadvantage is the difficulty to simulate more complex pumping systems, which are closer to real ones (for example: including an inlet pipe).

HIL is a graphical representation of the theoretical calculation. As can be seen above, it is a good way to visualize how the pumps react in theory when using different control methods. By using the same data provided for the theoretical calculation (system, power and pump curves and the system specification datasheet), the LabView program runs for a given period of time and logs the specific energy values.
4.4.4. Measured data from pump stations

Data is taken from pump stations with the help of different instrumentation. Based on provided data, an algorithm that can calculate specific energy is used. It uses as inputs water level (logged every 60 seconds via a logging device), as seen in figure 21, and energy values (logged every 60 minutes via a logging device). The sampling times are different for the two parameters because water level has rapid variation of value while the energy varies very slowly.

Steps in \( E_{sp} \) algorithm:

1) Calculate the water level increase/decrease difference and save it in a vector (results in positive and negative values, corresponding to water level raise and pumping cycle).

2) The negative values are replaced by zero, making way for the new approximated values of the relative height.

3) Delete single value (if there is just one value, positive or zero between at least two values of the other type, the value is replaced by the average of the adjacent samples, because it is considered an error in measurement); this step is used as a filter, as seen in figure 22.
4) Calculate the average height for the pumping cycle based on the adjacent positive values from the vector, as seen in figure 23:

$$X = \frac{(a + b + c + d + e + f)}{6} \quad \text{(Eq.25)}$$

Where:

- \(a, b, c\) are the last three positive values before a series of zero.
- \(d, e, f\) are the first three positive values after a series of zero.
- \(X\) represents the range of zeros between the positive values.

5) Replace the values of zero with the above calculated values of average height during pumping (because a constant inflow is considered during each pumping cycle).

6) Sum all the elements of the vector, resulting in a total relative height.

7) By using equation 9, calculate the absolute value of the pumped volume, as seen in figure 24:
Furthermore, area usually follows:

\[ A = \pi * R^2 \]  

(Eq.26)

Or

\[ A = w * h \]  

(Eq.27)

Where:

- R is the radius of the sump [m]
- A is the sump area [m²]
- w is the width [m]
- h is the height [m]

Figure 24: Volume calculation

8) Calculate the difference in energy between the first and the last collected data from the VFD’s internal energy counter during the period put in discussion.

9) Calculate the absolute value of the specific energy.

This method has advantages like the lack of need of expensive instrumentation to measure and record input data that is needed to perform its calculation steps, the fact that it is an easy and reliable solution for both constant and variable inflow and that it can be used by anyone that does not have prior knowledge of flow measurement.
Some of its disadvantages are that errors in input data can give wrong results and that it relies on the accuracy of level measurement, so it needs a short logging time (each second) between values to provide more accurate results.

For data measuring, instrumentation was used to record values from the internal energy meter of the VFD and the level sensor. Energy was saved and level data for both control methods during different periods of time. With the algorithm presented above, specific energy was calculated for each period. The system curve (total head and static head) was measured by running the pumps at different frequencies and recording the flow with a flow meter. By having the theoretical pump curves, each flow’s corresponding head was obtained and the system curve was calculated.

### 4.5. Methods of validating volume and energy results

There are two other methods of volume calculation that are taken into consideration and constitute a comparison basis for the solution of the algorithm:

1) **Timer method**

This is one way of calculating the outflow. Firstly, the time that has passed since the pump started to pump until it stopped is recorded. By knowing the value of the sump area, the difference between start and stop levels and the inflow (which can be an instantaneous value read from a flow meter installed on the inlet pipe or can be calculated based on the time for a certain volume of the sump filled in when pumps do not run), the pumped volume can be calculated, as seen in figure 25.

\[
V = A \times h + Q \times t
\]  
(Eq.28)

Where:

- **V** is the pumped volume [m³]
- **A** is the sump area [m²]
- **h** is the “pumped height” [m]
- **Q** is the inflow [l/s]
- **t** is the time between start and stop level [s]
2) Flow measurement

This is a method of quantifying the fluid movement. It is divided into different types, because each type needs specific considerations, i.e. precision, cost and use of gathered information [14].

There are many ways of classifying the types of liquid flow meters. One way is by their individual name under general characteristics [14]:

- Head meters:
  a. Orifice
  b. Flow nozzle
  c. Venturi
  d. Elbows

- Linear meters:
  e. Non-intrusive
     i. Coriolis
     ii. Ultrasonic (example: Doppler or Transit time)
  f. Intrusive
     i. Multiphase
     ii. Positive displacement
     iii. Turbine, liquid
     iv. Vortex shedding
The energy output from the algorithm is compared with one other method:

3) Electrical power analyzer method

This method is used to measure various parameters of a single or three-phase electrical system [24], as seen in figure 26. A three-phase electrical system is the most common way to transfer power. It uses less conductor material and it is cheaper than single-phase or two-phase equivalents for the same voltage [26].

![Three-phase systems](image)

**Figure 26: Three-phase systems**

Electrical power analyzers can measure instantaneous power (W), instantaneous or reactive volt-amperes (VA or VAr), frequency (Hz), energy (Wh), harmonic distortion, etc. [25]. The instrument gives the possibility to save all data, which can be further displayed and analyzed [24]. In addition to the fact that power analyzers are reliable devices, they also have the advantage of being cheap and accessible all around the world. There are different types of power analyzers.

The $E_{sp}$ algorithm is tested in two pump stations (in the laboratory and on the field) where there is full control of the measurement devices. For a validation of the results, its output was compared with other methods, presented below.

For volume comparison, a flow measurement method was used. It requires presence on the site. Different instrumentation was used for each of the two cases. Both of the devices were placed on the outlet pipe to measure the outflow. Finally, calculation steps from above were followed and a value of the pumped volume was computed, which was further compared with the $E_{sp}$ algorithm.
For the energy part a power analyzer was used as a comparison method. The energy values were saved via a logging device, i.e. Netbiter.
5. Results

This chapter presents the results obtained during the testing period. It includes different scenarios simulated into the sensitivity analysis and also values obtained after using the four methods of computing specific energy. The accuracy of the sensors is assumed to be 100%. More information about the “Test Generation” tool can be found as an attachment.

5.1. Results from the algorithm's sensitivity analysis

Calculation results from the sensitivity analysis of the algorithm are shown below. By choosing a start level of 0.75 m, a stop level of 0.25 m and an area of 2.54 m², the theoretical value of the volume between the two levels becomes 1.27 m³.

By isolating one by one the parameters mentioned above, several scenarios were developed to show what the impact of each is:

1) Logging time (60 seconds vs. 1 second)
   a) Short water rise time (t_r) – short pumping cycle (t_p) i.e. each cycle takes less than 180 seconds. (t_r = 128 s, t_p = 128 s, Q_in = 10 l/s, Q_pump = 20 l/s)

   Theoretic result: \( V = 10 \times 60 \times 60 \times 24 = 864 \text{ m}^3/\text{day} \)

   Algorithm calculation (sample every 60 s): \( V = A \times h = 2.54 \times 263.80 = 670 \text{ m}^3/\text{day} \)

   Algorithm calculation (sample every 1 s): \( V = A \times h = 2.54 \times 340 = 864 \text{ m}^3/\text{day} \)

   Error:
   - Theoretic vs. algorithm calculation (sample every 60 s): 22.44%
   - Theoretic vs. algorithm calculation (sample every 1 s): 0%
Figure 27: Water level for one hour [1st graph – sample every 1 s, 2nd graph – sample every 1 min]

Explanation: When both cycles are running in less than 180 seconds, there is not enough sample data to do a proper calculation, since the pumping cycle is based on an average of positive values (water level rise), which need to be at least three before and after it. If the logging happens every second, even with a short cycle there are enough samples to compute a more accurate result than in the case of saving data every 60 seconds.

b) Short water rise time ($t_r$) – long pumping cycle ($t_p$), i.e. water rise takes less than 180 seconds, pumping cycle takes more than 180 seconds. ($t_r \approx 128$ s, $t_p \approx 631$ s, $Q_{in} = 10$ l/s, $Q_{pump} = 12$ l/s)

Theoretic result: $V = 10 \times 60 \times 60 \times 24 = 864$ m$^3$/day

Algorithm calculation (sample every 60 s): $V = A \times h = 2.54 \times 243.60 = 619$ m$^3$/day

Algorithm calculation (sample every 1 s): $V = A \times h = 2.54 \times 339 = 861$ m$^3$/day

Error:

- Theoretic vs. algorithm calculation (sample every 60 s): 28.35%
- Theoretic vs. algorithm calculation (sample every 1 s): 0.30%
Explanation: As in case a), by not having three samples before and after the pumping cycle, it is not possible to calculate a proper average that can replace the negative values. In cases with a longer pumping cycle more negative values are replaced by the average of the positive ones, so the error increases.

c) Long water rise time ($t_r$) – Short pumping cycle ($t_p$), i.e. water rise takes more than 180 seconds, pumping cycle takes less than 180 seconds. ($t_r \approx 631 \text{ s}, t_p \approx 128 \text{ s}, Q_{in} = 2 \text{ l/s}, Q_{pump} = 12 \text{ l/s}$)

Theoretic result: $V = 2 \times 60 \times 60 \times 24 = 173 \text{ m}^3/\text{day}$

Algorithm calculation (sample every 60 s): $V = A \times h = 2.54 \times 66.87 = 170 \text{ m}^3/\text{day}$

Algorithm calculation (sample every 1 s): $V = A \times h = 2.54 \times 68.03 = 173 \text{ m}^3/\text{day}$

Error:
- Theoretic vs. algorithm calculation (sample every 60 s): 1.73%
- Theoretic vs. algorithm calculation (sample every 1 s): 0%
Figure 29: Water level for one hour [1st graph – sample every 1 s, 2nd graph – sample every 1 min]

Explanation: Because there are two (for samples logged every 60 seconds) or more values (for samples logged every second) corresponding to the pumping cycle and more than three values corresponding to the water level rise, there is a smaller error between theoretical results and algorithm calculation than in case a) or b).

d) Long water rise time ($t_r$) – long pumping cycle ($t_p$), i.e. both cycles take more than 180 seconds each. ($t_r \approx 631$ s, $t_p \approx 631$ s, $Q_m = 2$ l/s, $Q_{pump} = 4$ l/s)

Theoretic result: $V = 2 \times 60 \times 60 \times 24 = 173 \text{ m}^3/\text{day}$

Algorithm calculation (sample every 60 s): $V = A \times h = 2.54 \times 64.10 = 163 \text{ m}^3/\text{day}$

Algorithm calculation (sample every 1 s): $V = A \times h = 2.54 \times 68.03 = 173 \text{ m}^3/\text{day}$

Error:
- Theoretic vs. algorithm calculation (sample every 60 s): 5.78%
- Theoretic vs. algorithm calculation (sample every 1 s): 0%
Explanation: Because there are more than two samples corresponding to the pumping cycle, the efficiency of the algorithm when data is logged every 60 seconds decreases, when compared with case c).

e) Very long water rise time ($t_r$) – very long pumping cycle ($t_p$), i.e. both cycles take more than one hour each. ($t_r \approx 3600$ s, $t_p \approx 3600$ s, $Q_{in} = 0.25$ l/s, $Q_{pump} = 0.5$ l/s)

Theoretic result: $V = 0.25 \times 60 \times 60 \times 24 = 22$ m$^3$/day

Algorithm calculation (sample every 60 s): $V = A \times h = 2.54 \times 8.39 = 21$ m$^3$/day

Algorithm calculation (sample every 1 s): $V = A \times h = 2.54 \times 8.51 = 22$ m$^3$/day

Error:

- Theoretic vs. algorithm calculation (sample every 60 s): 4.54%
- Theoretic vs. algorithm calculation (sample every 1 s): 0%
Explanation: Longer time for both of the cycles increases the efficiency of the algorithm for the case data is logged every 60 seconds, when having a constant inflow, because of more sample data to do the average. For the case data is logged every second, it does not bring any improvement in efficiency, because there are already a lot of samples to work with, even if there is a short cycle.

2) **Constant inflow vs. variable inflow**

a) Small interval of variation of inflow every 10 seconds. \( (Q_m \in (10, 15) \text{ l/s}, Q_{pump} = 20 \text{ l/s}, \text{cycle time is shorter than the inflow variation}) \)

Theoretic result: \( V = 1079 \text{ m}^3/\text{day} \)

Algorithm calculation (sample every 1 s): \( V = A \cdot h = 2.54 \cdot 421.63 = 1071 \text{ m}^3/\text{day} \)

Error:

- Theoretic vs. algorithm calculation (sample every 1 s): 0.74%
Explanation: Because the variation interval is small and the cycle time is shorter than the inflow variation, the error tends to be small. There can be multiple inflow variation periods during one cycle, but because they are small, the average value that is replacing the pumping cycle is not affected too much.

b) Small interval of variation of inflow every 60 seconds. ($Q_m \in (10, 15)$ l/s, $Q_{pump} = 20$ l/s, cycle time is close to the inflow variation)

Theoretic result: $V = 1081$ m$^3$/day

Algorithm calculation (sample every 1 s): $V = A \times h = 2.54 \times 423.64 = 1076$ m$^3$/day

Error:

- Theoretic vs. algorithm calculation (sample every 1 s): 0.5%
Explanation: Because the variation interval is small and the cycle time is closer to the inflow variation period, the error tends to be smaller than in case a). There is only one inflow variation period during one cycle, so there is only one average value that is replacing the pumping cycle.

c) Small interval of variation of inflow every 100 seconds. \((Q_{in} \in (10, 15) \text{ l/s}, Q_{pump} = 20 \text{ l/s}, \text{ cycle time is longer than the inflow variation})\)

Theoretic result: \(V = 1098 \text{ m}^3/\text{day}\)

Algorithm calculation (sample every 1 s): \(V = A * h = 2.54 * 429.21 = 1090 \text{ m}^3/\text{day}\)

Error:
- Theoretic vs. algorithm calculation (sample every 1 s): 0.72%

![Figure 34: Water level for 10 minutes](image1)

Explanation: Because the variation interval is small and the cycle time is longer than the inflow variation, the error tends to be bigger than in case b). There is one inflow variation period during two or more cycles, so during one cycle inflow values can change, thus affecting the average that replaces the samples from the pumping cycle.

d) Big interval of variation of inflow every 10 seconds. \((Q_{in} \in (5, 35) \text{ l/s}, Q_{pump} = 40 \text{ l/s}, \text{ cycle time is shorter than the inflow variation})\)

Theoretic result: \(V = 1720 \text{ m}^3/\text{day}\)
Algorithm calculation (sample every 1 s): \[ V = A \times h = 2.54 \times 669.48 = 1700 \, \text{m}^3/\text{day} \]

Error:

- Theoretic vs. algorithm calculation (sample every 1 s): 1.16%

![Figure 35: Water level for 10 minutes [big interval of variation of inflow every 10 seconds]](image)

Explanation: Because the variation interval is big and the cycle time is shorter than the inflow variation, there are multiple inflow variation periods during one cycle. When compared with case a), the error tends to increase, but it is still small.

e) Big interval of variation of inflow every 60 seconds. \( Q_{in} \in (5, 35) \, \text{l/s}, \, Q_{pump} = 40 \, \text{l/s}, \, \text{cycle time is close to the inflow variation} \)

Theoretic result: \( V = 1685 \, \text{m}^3/\text{day} \)

Algorithm calculation (sample every 1 s): \[ V = A \times h = 2.54 \times 663.26 = 1685 \, \text{m}^3/\text{day} \]

Error:

- Theoretic vs. algorithm calculation (sample every 1 s): 0%
Explanation: Even if the variation interval is big, because the cycle time is closer to the inflow variation period, the error tends to be small. There is only one inflow variation period during one cycle, so there is only one average value that is replacing the pumping cycle.

f) Big interval of variation of inflow every 100 seconds. \((Q_{\text{in}} \in (5, 35) \text{ l/s, } Q_{\text{pump}} = 40 \text{ l/s, cycle time is longer than the inflow variation})\)

Theoretic result: \(V = 1706 \text{ m}^3/\text{day}\)

Algorithm calculation (sample every 1 s): \(V = A \times h = 2.54 \times 636.65 = 1617 \text{ m}^3/\text{day}\)

Error:

- Theoretic vs. algorithm calculation (sample every 1 s): 5.21%
Explanation: Because the variation interval is big and the cycle time is longer than the inflow variation, the error tends to be bigger than in all the other cases. There is one big inflow variation period during two or more cycles, so the average calculation is affected.

3) Constant pump outflow vs. pump outflow linear dependent on the head

a) Small inflow & outflow (Q_{in} = 0.5 l/s):

Theoretic result: \( V = 0.5 \times 60 \times 60 \times 24 = 43 \text{ m}^3/\text{day} \)

Algorithm calculation, constant pump outflow (Q_{pump} = 1 l/s):
\[
V = A \times h = 2.54 \times 17.00 = 43 \text{ m}^3/\text{day}
\]

Algorithm calculation, pump outflow linear dependent on the head (set Q_{pump} \in [0.6, 1] l/s, Q_{pump}(i) = 0.4 + 0.8 \times \text{level}(i-1), for i \in (2, 86400)):
\[
V = A \times h = 2.54 \times 16.88 = 43 \text{ m}^3/\text{day}
\]

Error:
- Theoretic vs. algorithm calculation with constant pump outflow: 0%
- Theoretic vs. algorithm calculation with pump outflow linear dependent on the head: 0%
Explanation: For long cycles having a constant pump outflow produces better results, because of the average approximation.

b) Large inflow & outflow ($Q_{in} = 10 \, l/s$):

Theoretic result: $V = 10 \times 60 \times 60 \times 24 = 864 \, m^3/day$

Algorithm calculation, constant pump outflow ($Q_{pump} = 20 \, l/s$):

$$ V = A \times h = 2.54 \times 340.15 = 864 \, m^3/day $$

Algorithm calculation, pump outflow linear dependent on the head (set $Q_{pump} \in [15, 20] \, l/s$, $Q_{pump}(i) = 12.5 + 10 \times \text{level}(i-1)$, for $i \in (2, 86400)$):

$$ V = A \times h = 2.54 \times 340.15 = 864 \, m^3/day $$

Error:

- Theoretic vs. algorithm calculation with constant pump outflow: 0%
- Theoretic vs. algorithm calculation with pump outflow linear dependent on the head: 0%
Figure 39: Water level for 10 minutes [large inflow, large outflow]

Explanation: Because the process has an increased speed and compared to case a) the number of samples decreases, when the average is done it can be seen similar or very close results between constant pump outflow and pump outflow which is linear dependent on the head.

c) Very large inflow & outflow (Q_{in} = 20 l/s):

Theoretic result: \( V = 20 \times 60 \times 60 \times 24 = 1728 \text{ m}^3/\text{day} \)

Algorithm calculation with constant pump outflow (Q_{pump} = 40 l/s):

\[
V = A \times h = 2.54 \times 679.8031 = 1772 \text{ m}^3/\text{day}
\]

Algorithm calculation with pump outflow linear dependent on the head (set Q_{pump} \in [25, 40] l/s, Q_{pump}(i) = 17.5 + 30 \times \text{level}(i-1), \text{for } i \in (2, 86400)):

\[
V = A \times h = 2.54 \times 679.39 = 1726 \text{ m}^3/\text{day}
\]

Error:

- Theoretic vs. algorithm calculation with constant pump outflow: -2.54%
- Theoretic vs. algorithm calculation with pump outflow linear dependent on the head: 0.11%
Explanation: A greater increase of the cycle time gives a better approximation of the case where the pump outflow is linear dependent on the head, because there are more samples in the pumping cycle to replace with the average.

4) Combination of parameters

a) Small interval of variation of inflow every 10 seconds (Q_{in} \in (0, 2) \text{ l/s}, Q_{pump} \in [2.1, 5] \text{ l/s},
Q_{pump}(i) = 0.65 + 5.8 * \text{level}(i-1) , \text{ for } i \in (2, 86400)):

Theoretic result: V = 86 \text{ m}^3/\text{day}

Algorithm calculation (sample every 60 s): V = A * h = 2.54 * 32.82 = 83 \text{ m}^3/\text{day}

Error:

- Theoretic vs. algorithm calculation (sample every 60 s): 3.48%
Explanation: Because the interval of variation is small, the algorithm’s efficiency is not decreased too much, and the average calculation is precise, having calculation results close to the theoretical ones.

b) Big interval of variation of inflow every 10 seconds ($Q_{in} \in (0, 20)$ l/s, $Q_{pump} \in [25, 35]$ l/s, $Q_{pump}(i) = 20 + 20 \times \text{level}(i-1)$, for $i \in (2, 86400)$):

Theoretic result: $V = 867$ m$^3$/day
Algorithm calculation (sample every 60 s): $V = A \times h = 2.54 \times 248.91 = 632$ m$^3$/day
Error:
- Theoretic vs. algorithm calculation (sample every 60 s): 27.10%
Explanation: A rapid variation of the inflow connected with a large interval of variation, a logging time of 60 seconds and a pump outflow linear dependent on the head greatly increase the error, especially when the variation speed is shorter than the cycle time.

Furthermore, table 1 presents the results of the tests conducted above. In the “Parameter” field there are key factors which influence the output of the volume calculation part. Fields “1st Characteristic” and “2nd Characteristic” represent specific test conditions for each test.

In the “Theoretical result” part, the theoretical pumped volume is calculated. “Algorithm result” gives the output of the algorithm and “Error” shows the difference in percentage between results from algorithm and theory.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>1st Characteristic</th>
<th>2nd Characteristic</th>
<th>Theoretical result [kWh/m^3]</th>
<th>E_{ip} Algorithm [kWh/m^3]</th>
<th>Error_{Alg-Th} [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Logging time</td>
<td>t_{rise} &lt; 180 s, t_{pumping} &lt; 180 s</td>
<td>t_{log} = 1 s</td>
<td>864</td>
<td>864</td>
<td>0.00</td>
</tr>
<tr>
<td></td>
<td></td>
<td>t_{log} = 60 s</td>
<td></td>
<td>670</td>
<td>22.44</td>
</tr>
<tr>
<td></td>
<td>t_{rise} &lt; 180 s, t_{pumping} &gt; 180 s</td>
<td>t_{log} = 1 s</td>
<td>864</td>
<td>861</td>
<td>0.30</td>
</tr>
<tr>
<td></td>
<td></td>
<td>t_{log} = 60 s</td>
<td></td>
<td>619</td>
<td>28.35</td>
</tr>
<tr>
<td></td>
<td>t_{rise} &gt; 180 s, t_{pumping} &lt; 180 s</td>
<td>t_{log} = 1 s</td>
<td>173</td>
<td>173</td>
<td>0.00</td>
</tr>
<tr>
<td></td>
<td></td>
<td>t_{log} = 60 s</td>
<td></td>
<td>170</td>
<td>1.73</td>
</tr>
<tr>
<td></td>
<td>t_{rise} &gt; 180 s, t_{pumping} &gt; 180 s</td>
<td>t_{log} = 1 s</td>
<td>173</td>
<td>173</td>
<td>0.00</td>
</tr>
<tr>
<td></td>
<td></td>
<td>t_{log} = 60 s</td>
<td></td>
<td>163</td>
<td>5.78</td>
</tr>
<tr>
<td></td>
<td>t_{rise} &gt;&gt; 180 s, t_{pumping} &gt;&gt; 180 s</td>
<td>t_{log} = 1 s</td>
<td>22</td>
<td>22</td>
<td>0.00</td>
</tr>
<tr>
<td></td>
<td></td>
<td>t_{log} = 60 s</td>
<td></td>
<td>21</td>
<td>4.54</td>
</tr>
<tr>
<td>Variable</td>
<td>Q_{in} ∈ [10, 15] l/s</td>
<td>t_{variation} = 10 s</td>
<td>1079</td>
<td>1071</td>
<td>0.74</td>
</tr>
<tr>
<td>Inflow</td>
<td></td>
<td>t_{variation} = 60 s</td>
<td>1081</td>
<td>1076</td>
<td>0.50</td>
</tr>
<tr>
<td></td>
<td></td>
<td>t_{variation} = 100 s</td>
<td>1098</td>
<td>1090</td>
<td>0.72</td>
</tr>
<tr>
<td></td>
<td>Q_{in} ∈ [5, 35] l/s</td>
<td>t_{variation} = 10 s</td>
<td>1720</td>
<td>1700</td>
<td>1.16</td>
</tr>
<tr>
<td></td>
<td></td>
<td>t_{variation} = 60 s</td>
<td>1685</td>
<td>1685</td>
<td>0.00</td>
</tr>
<tr>
<td></td>
<td></td>
<td>t_{variation} = 100 s</td>
<td>1706</td>
<td>1617</td>
<td>5.21</td>
</tr>
<tr>
<td>Pump outflow</td>
<td>Q_{in} = Q_{out} = 0.5 l/s</td>
<td>Q_{pump} = 1 l/s</td>
<td>43</td>
<td>43</td>
<td>0.00</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Q_{pump} ∈ [0.6, 1] l/s</td>
<td></td>
<td>43</td>
<td>0.00</td>
</tr>
<tr>
<td></td>
<td>Q_{in} = Q_{out} = 10 l/s</td>
<td>Q_{pump} = 10 l/s</td>
<td>864</td>
<td>864</td>
<td>0.00</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Q_{pump} ∈ [15, 20] l/s</td>
<td></td>
<td>864</td>
<td>0.00</td>
</tr>
<tr>
<td></td>
<td>Q_{in} = Q_{out} = 20 l/s</td>
<td>Q_{pump} = 20 l/s</td>
<td>1728</td>
<td>1772</td>
<td>-2.54</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Q_{pump} ∈ [25, 40] l/s</td>
<td></td>
<td>1726</td>
<td>0.11</td>
</tr>
<tr>
<td>Combined</td>
<td>t_{log} = 60 s, Q_{in} ∈ [0, 2] l/s, t_{variation} = 10 s, Q_{pump} ∈ [2.1, 5] l/s</td>
<td></td>
<td>86</td>
<td>83</td>
<td>3.48</td>
</tr>
<tr>
<td>parameters</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>t_{log} = 60 s, Q_{in} ∈ [0, 20] l/s, t_{variation} = 10 s, Q_{pump} ∈ [25, 35] l/s</td>
<td></td>
<td>867</td>
<td>632</td>
<td>27.10</td>
</tr>
</tbody>
</table>
5.2. Results of specific energy evaluation

This subchapter gives an overview of the testing facilities and the test conditions used when the calculations were performed.

5.2.1. Description of pump stations

1) STR – laboratory station:

Data provided by the system specification datasheet:

- Sump height is 2.4 m
- Sump diameter is 1.6 m, resulting in an area of 2.01 m²
- Station is equipped with 2 N3102 SH pumps, a SRC311 variable frequency drive, and a hydrostatic pressure sensor (Pumps: N3102 SH 4.2 kW, 400 V, 8.1 A; Drive: SRC311 15kW, 400 V, 30 A, software v2.0)
- Outflow measurement: NivuSonic CO 100 portable flow meter [30]
- Data is logged with a Netbiter EC220 device

Values measured for the tests:

- System curve: Total head is 12.7 m, Static head is 0.8 m
- Average outflow at 50 Hz is 20.4 l/s

Test conditions:

- Clean water
- Start level is 1.2 m; Stop level is 0.6 m
- Constant inflow of 3.5 l/s (Set for both HIL and measured data)

2) Sigtuna – municipal pump station:

Data provided by the system specification datasheet:

- Sump type is TOP 150 L
- Sump height is 4.1 m
- Sump diameter is 1.8 m, resulting in an area of 2.54 m²
- Inlet pipe DN315: level 0.6 m, angle 270 degrees, diameter: 0.31m
- Station is equipped with 2 N3153 HT pumps, a SRC311 variable frequency drive, a mixer and a 3.75 m hydrostatic pressure sensor (Pumps: N3153 HT 13.5 kW, 400 V, 27 A; Drive: SRC311 15kW, 400 V, 30 A, software v2.0)
- Outflow measurement: Optiflux 2000 D flow meter [29] + WMpro monitoring device [31]
- Data is logged with a Netbiter EC220 device

Values measured for the tests:

- System curve: Total head is 24 m, Static head is 9.6 m
- Average outflow at 50 Hz is 36 l/s

Test conditions:

- Wastewater
- Start level is 0.75 m; Stop level is 0.25 m
- Variable inflow between 2.1 – 2.7 l/s (For HIL inflow is set as constant at 2.3 l/s)

5.2.2. Results from theoretical calculation

Based on the pump curves and system specification, the specific energy is calculated for DOL and VFD control.

1) STR – laboratory station:

Table 2 shows what type of pumps are used in the laboratory station along with their electrical specification and type of impeller. More information can be found in the first part of appendix 3.

<table>
<thead>
<tr>
<th>Pump</th>
<th>N 3102 SH 3~ 2p</th>
</tr>
</thead>
<tbody>
<tr>
<td>Motor</td>
<td>N3102.181 18-10-2AL-W 4.2kW</td>
</tr>
<tr>
<td>Impeller</td>
<td>255 152mm</td>
</tr>
</tbody>
</table>
In figure 43, the system curve can be seen and figure 44 gives an overview of the theoretical specific energy curve in the STR station. The frequencies taken into account are in the range 50 Hz to 8 Hz.
Table 3 presents what are the theoretical frequencies, flows, heads, efficiencies, total input powers and theoretical specific energies for DOL and VFD control (optimal frequency). In theory, the smallest specific energy use is at 10 Hz, but the VFD drive was limited at 30 Hz, so this value is considered as a comparison basis. More information can be found in the second part of appendix 3.

<table>
<thead>
<tr>
<th>Pump</th>
<th>DOL ( \text{TTH} )</th>
<th>VFD ( \text{TTH} ) for optimal frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency [Hz]</td>
<td>50</td>
<td>30</td>
</tr>
<tr>
<td>Outflow [l/s]</td>
<td>20.42</td>
<td>11.86</td>
</tr>
<tr>
<td>Total head [m]</td>
<td>12.72</td>
<td>4.82</td>
</tr>
<tr>
<td>Total efficiency [%]</td>
<td>50.23</td>
<td>51.05</td>
</tr>
<tr>
<td>Total input power [kW]</td>
<td>5.07</td>
<td>1.10</td>
</tr>
<tr>
<td>Specific energy [kWh/m³]</td>
<td>0.0690</td>
<td>0.0270</td>
</tr>
</tbody>
</table>

By comparing the specific energy for DOL and VFD control, it was found out that the theoretical savings are:

- \( \text{Savings}_{\text{VFD - DOL}} = 60.86\% \)

2) Sigtuna – municipal pump station:

Table 2 shows what type of pumps are used in Sigtuna pump station along with their electrical specification and type of impeller. More information can be found in the first part of appendix 4.

<table>
<thead>
<tr>
<th>Table 4: Pump type - Sigtuna</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pump</td>
</tr>
<tr>
<td>Motor</td>
</tr>
<tr>
<td>Impeller</td>
</tr>
</tbody>
</table>

In figure 45, the system curve can be seen and figure 46 gives an overview of the theoretical specific energy curve in the STR station. The frequencies taken into account are from 50 Hz to 28 Hz.
Figure 45: System & pump curves at different frequencies – Sigtuna

Figure 46: Theoretical specific energy curve - Sigtuna
Table 5 presents what are the theoretical frequencies, flows, heads, efficiencies, total input powers and theoretical specific energies for DOL and for VFD control (optimal frequency). In theory, the smallest specific energy is at 32 Hz. More information can be found in the second part of appendix 4.

Table 5: Theoretic specific energy for different values of the frequency - Sigtuna

<table>
<thead>
<tr>
<th>1 Pump</th>
<th>DOL_{TH}</th>
<th>VFD_{TH} optimal frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency [Hz]</td>
<td>50</td>
<td>32</td>
</tr>
<tr>
<td>Outflow [l/s]</td>
<td>35.84</td>
<td>13.19</td>
</tr>
<tr>
<td>Total head [m]</td>
<td>23.88</td>
<td>11.53</td>
</tr>
<tr>
<td>Total efficiency [%]</td>
<td>66.06</td>
<td>55.29</td>
</tr>
<tr>
<td>Total input power [kW]</td>
<td>12.71</td>
<td>2.70</td>
</tr>
<tr>
<td>Specific energy [kWh/m^3]</td>
<td>0.0980</td>
<td>0.0570</td>
</tr>
</tbody>
</table>

By comparing the specific energy for DOL and VFD control, it was found out that the theoretical savings are:

- \text{Savings}_{VFD - DOL} = 41.83\%

5.2.3. Results from simplified theoretical model

1) STR – laboratory station:

The model is based on the rated power \(P = 4.2\ kW\), the formulas and calculation steps from chapter 4.4.2.
As seen in figure 47, the potential savings that the simplified model gives are around 62%, for the STR laboratory station:

- $\text{Savings}_{\text{VFD-DOL}} = 62\%$

2) Sigtuna – municipal pump station:

The model is based on the rated power ($P = 13.5$ kW), the formulas and calculation steps from chapter 4.4.2.
As seen in figure 48, the potential savings that the simplified model gives are around 38%, for Sigtuna municipal station:

- \[ \text{Savings}_{\text{VFD - DOL}} = 38\% \]

### 5.2.4. Results from HIL

HIL tool uses as input the values and conditions mentioned in chapter 4.4.3. Both laboratory and municipal stations are used as comparison objects, because there is sufficient information to
simulate starting and running conditions. More information about what the inputs and the outputs are can be found in the attachments part.

1) **STR – laboratory station:**

**VFD control:**
- Test has been done between 2013-09-20 at 16:00 and 2013-09-23 at 9:10.
- Pump 1 is running, pump 2 is stopped.

Table 6 presents the logged energy and pumped volume values, the calculated specific energy and optimal frequency within HIL.

<table>
<thead>
<tr>
<th>Date (mm-dd)</th>
<th>09-20 to 09-23</th>
</tr>
</thead>
<tbody>
<tr>
<td>Optimal frequency [Hz]</td>
<td>30</td>
</tr>
<tr>
<td>Energy use [kWh]</td>
<td>31.19</td>
</tr>
<tr>
<td>Pumped volume [m$^3$]</td>
<td>815.28</td>
</tr>
<tr>
<td>Specific energy [kWh/m$^3$]</td>
<td>0.0383</td>
</tr>
</tbody>
</table>

**DOL control:**
- Test has been done between 2013-09-20 at 9:15 and 2013-09-20 at 16:25.
- Pump 1 is running, pump 2 is stopped.

Table 7 presents the logged energy and pumped volume values, the calculated specific energy and optimal frequency within HIL.

<table>
<thead>
<tr>
<th>Date (mm-dd)</th>
<th>09-23</th>
</tr>
</thead>
<tbody>
<tr>
<td>Optimal frequency [Hz]</td>
<td>50</td>
</tr>
<tr>
<td>Energy use [kWh]</td>
<td>5.99</td>
</tr>
<tr>
<td>Pumped volume [m$^3$]</td>
<td>89.77</td>
</tr>
<tr>
<td>Specific energy [kWh/m$^3$]</td>
<td>0.0660</td>
</tr>
</tbody>
</table>

**Comparison between DOL and VFD control:**

$\text{Savings}_{\text{VFD - DOL}} = 41.96\%$
2) Sigtuna – municipal station

VFD control:
- Test has been done between 2013-09-24 at 10:05 and 2013-09-25 at 11:20.
- When one pump is running, one pump is in standby.

Table 8 presents the logged energy and pumped volume values, the calculated specific energy and optimal frequency within HIL.

<table>
<thead>
<tr>
<th>Date (mm-dd)</th>
<th>Pump 1</th>
<th>Pump 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Optimal frequency [Hz]</td>
<td>32</td>
<td>32</td>
</tr>
<tr>
<td>Energy use [kWh]</td>
<td>8.23</td>
<td>7.58</td>
</tr>
<tr>
<td>Pumped volume [m³]</td>
<td>109.06</td>
<td>99.31</td>
</tr>
<tr>
<td>Specific energy [kWh/m³]</td>
<td>0.0755</td>
<td>0.0763</td>
</tr>
</tbody>
</table>

DOL control:
- Test has been done between 2013-09-25 at 11:27 and 2013-09-25 at 17:00.
- When one pump is running, one pump is in standby.

Table 9 presents the logged energy and pumped volume values, the calculated specific energy and optimal frequency within HIL.

<table>
<thead>
<tr>
<th>Date (mm-dd)</th>
<th>Pump 1</th>
<th>Pump 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Optimal frequency [Hz]</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>Energy use [kWh]</td>
<td>2.45</td>
<td>1.86</td>
</tr>
<tr>
<td>Pumped volume [m³]</td>
<td>25.55</td>
<td>19.37</td>
</tr>
<tr>
<td>Specific energy [kWh/m³]</td>
<td>0.0960</td>
<td>0.0963</td>
</tr>
</tbody>
</table>

Comparison between DOL and VFD control:

P1: \( \text{Savings}_{\text{VFD - DOL}} = 21.35\% \)
P2: \( \text{Savings}_{\text{VFD - DOL}} = 20.76\% \)
Total: \( \text{Savings}_{\text{VFD - DOL}} = 21\% \)
5.2.5. Results from measured data

Data was measured in two different stations: STR laboratory station and Sigtuna municipal station. More information about the way data was collected can be found in the attachment part.

1) STR – laboratory station:

DOL control:
- Test has been done between 2013-08-14 at 00:01 and 2013-08-14 at 23:59.
- Pump 1 is running, pump 2 is stopped.

Table 10 presents the logged energy use and pumped volume values, the optimal frequency and the specific energy calculated with the $E_{i_p}$ algorithm, as seen in chapter 4.4.4.

<table>
<thead>
<tr>
<th>Date (mm-dd)</th>
<th>08-14</th>
</tr>
</thead>
<tbody>
<tr>
<td>Optimal frequency [Hz]</td>
<td>50</td>
</tr>
<tr>
<td>Energy use [kWh]</td>
<td>24.15</td>
</tr>
<tr>
<td>Pumped volume [m$^3$]</td>
<td>347.58</td>
</tr>
<tr>
<td>Specific energy [kWh/m$^3$]</td>
<td>0.0694</td>
</tr>
</tbody>
</table>

VFD control:
- Test has been done between 2013-08-15 at 15:01 and 2013-08-15 at 23:59.
- Pump 1 is running, pump 2 is stopped.

Table 11 presents the logged energy and pumped volume values, the calculated specific energy and optimal frequency with the $E_{i_p}$ algorithm.

<table>
<thead>
<tr>
<th>Date (mm-dd)</th>
<th>08-15</th>
</tr>
</thead>
<tbody>
<tr>
<td>Optimal frequency [Hz]</td>
<td>31</td>
</tr>
<tr>
<td>Energy use [kWh]</td>
<td>6.70</td>
</tr>
<tr>
<td>Pumped volume [m$^3$]</td>
<td>123.25</td>
</tr>
<tr>
<td>Specific energy [kWh/m$^3$]</td>
<td>0.0543</td>
</tr>
</tbody>
</table>
Comparison between specific energy with DOL and VFD control:

\[ \text{Savings}_{\text{VFD - DOL}} = 21.75\% \]

2) Sigtuna – municipal pump station:

VFD control:

- Test has been done between 2013-11-01 at 00:01 and 2013-11-06 at 23:59.
- Two pumps in parallel, when one is running the other one is in standby.

Table 12 presents the logged energy and pumped volume, the optimal frequency and the specific energy calculated with the \( E_{sp} \) algorithm, as seen in chapter 4.4.4.

<table>
<thead>
<tr>
<th>Date (mm-dd)</th>
<th>11-01</th>
<th>11-02</th>
<th>11-03</th>
<th>11-04</th>
<th>11-05</th>
<th>11-06</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy use/day [kWh]</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pump1</td>
<td>8.30</td>
<td>7.80</td>
<td>9.20</td>
<td>10.60</td>
<td>15.90</td>
<td>12.10</td>
</tr>
<tr>
<td>Pump2</td>
<td>7.90</td>
<td>7.90</td>
<td>8.40</td>
<td>9.70</td>
<td>14.60</td>
<td>11.60</td>
</tr>
<tr>
<td>Total</td>
<td>16.20</td>
<td>15.70</td>
<td>17.60</td>
<td>20.30</td>
<td>30.50</td>
<td>23.70</td>
</tr>
<tr>
<td>Pumped volume/day [m(^3)]</td>
<td>Total</td>
<td>165.85</td>
<td>167.98</td>
<td>181.27</td>
<td>213.33</td>
<td>304.32</td>
</tr>
<tr>
<td>( E_{sp} )/day [kWh/m(^3)]</td>
<td>Total</td>
<td>0.0977</td>
<td>0.0935</td>
<td>0.0971</td>
<td>0.0952</td>
<td>0.1002</td>
</tr>
</tbody>
</table>

In table 13 it can be seen what the optimal frequency, energy, outflow and specific energy per day are, all values being calculated with the \( E_{sp} \) algorithm.

<table>
<thead>
<tr>
<th>Pump 1</th>
<th>Pump 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Optimal frequency [Hz]</td>
<td>34</td>
</tr>
<tr>
<td>Average energy/day [kWh]</td>
<td>20.66</td>
</tr>
<tr>
<td>Average pumped volume/day [m(^3)]</td>
<td>214.37</td>
</tr>
<tr>
<td>Average specific energy/day [kWh/m(^3)]</td>
<td>0.0961</td>
</tr>
</tbody>
</table>

DOL control:

- Test has been done between 2013-11-07 at 00:01 and 2013-11-12 at 23:59.
- Two pumps in parallel, one running and one standby.

Table 14 presents the logged energy and pumped volume values and the calculated specific energy per day with the \( E_{sp} \) algorithm.
Table 14: DOL control with E_{sp} – Sigtuna

<table>
<thead>
<tr>
<th>Date (mm-dd)</th>
<th>11-07</th>
<th>11-08</th>
<th>11-09</th>
<th>11-10</th>
<th>11-11</th>
<th>11-12</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy use/day [kWh]</td>
<td>Pump1</td>
<td>15.70</td>
<td>11.70</td>
<td>12.10</td>
<td>16.30</td>
<td>13.90</td>
</tr>
<tr>
<td></td>
<td>Pump2</td>
<td>11.20</td>
<td>13.00</td>
<td>13.80</td>
<td>13.90</td>
<td>13.60</td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>26.90</td>
<td>24.70</td>
<td>25.90</td>
<td>30.20</td>
<td>27.50</td>
</tr>
<tr>
<td>Pumped volume/day [m^3]</td>
<td>Total</td>
<td>249.11</td>
<td>222.69</td>
<td>242.22</td>
<td>277.78</td>
<td>256.65</td>
</tr>
<tr>
<td>E_{sp}/day [kWh/m^3]</td>
<td>Total</td>
<td>0.1080</td>
<td>0.1109</td>
<td>0.1069</td>
<td>0.1087</td>
<td>0.1071</td>
</tr>
</tbody>
</table>

In table 15 it can be seen what the optimal frequency, energy, outflow and specific energy per day are, all values being calculated with the E_{sp} algorithm.

Table 15: Average values for DOL control - Sigtuna

<table>
<thead>
<tr>
<th></th>
<th>Pump 1</th>
<th>Pump 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Optimal frequency [Hz]</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>Average energy/day [kWh]</td>
<td>27.03</td>
<td></td>
</tr>
<tr>
<td>Average pumped volume/day [m^3]</td>
<td>249.62</td>
<td></td>
</tr>
<tr>
<td>Average specific energy/day [kWh/m^3]</td>
<td>0.1083</td>
<td></td>
</tr>
</tbody>
</table>

Comparison between specific energy with DOL and VFD control:

Savings_{VFD - DOL} = 11.2%

5.3 Results from comparing volume and energy values

This subchapter shows what the difference in results is when comparing several methods of volume and energy approximation.

5.3.1. Results after comparing volume values from different methods

1) STR – laboratory station:
   - Test 1 has been done between 2013-05-30 at 00:01 and 2013-06-01 at 23:59 (comparison between flow meter and specific energy calculation algorithm, while having a constant inflow: Q_{in} = 12 l/s).
   - Test 2 has been done between 2013-06-01 at 00:01 and 2013-06-01 at 23:59 (comparison between flow meter and specific energy calculation algorithm, while having a variable inflow: Q_{in} \in [12, 20] l/s).
- Pump 1 is running, pump 2 is stopped.
- A Krohne Aquaflux magnetic flow meter was used [33], which was installed on the outlet.
- Inflow is set via a controller, which handles four pumps in the buffer.

Table 16 shows results from test 1 and test 2. It can be seen that there is a big discrepancy between the value calculated with the $E_{sp}$ algorithm and the one measured by the flow meter, which has an accuracy of $\pm 1$. Later on, it was found out that there was a problem with the flow meter, so the accuracy of the results cannot be determined.

<table>
<thead>
<tr>
<th>Test number</th>
<th>$E_{sp}$ Algorithm [m$^3$]</th>
<th>Flow meter [m$^3$]</th>
<th>Error [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test 1</td>
<td>696.77</td>
<td>1036.8</td>
<td>32.80</td>
</tr>
<tr>
<td>Test 2</td>
<td>685.04</td>
<td>1364.56</td>
<td>50.00</td>
</tr>
</tbody>
</table>

2) Sigtuna – municipal pump station:

- Test 3 has been done between 2013-06-26 at 00:01 and 2013-07-08 at 23:59 (comparison between flow meter and $E_{sp}$ algorithm).
- Pump 1 is running, pump 2 is stopped.
- A Krohne OPTIFLUX 2000 magnetic flow sensor was used and data was collected through a network with a WMpro monitoring device.

Table 17 shows results from test 3. It can be seen that the error between the value provided by the $E_{sp}$ algorithm and the one recorded by the flow meter is less than 1%.

<table>
<thead>
<tr>
<th>Test 3</th>
<th>Flow meter [m$^3$]</th>
<th>$E_{sp}$ Algorithm [m$^3$]</th>
<th>Error [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial value of the counter</td>
<td>7836.36</td>
<td>1656.70</td>
<td>0.31</td>
</tr>
<tr>
<td>Final value of the counter</td>
<td>9498.26</td>
<td>1656.70</td>
<td>0.31</td>
</tr>
<tr>
<td>Result</td>
<td>1661.90</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
5.3.2. Results after comparing energy values

The energy comparison test was done in the STR laboratory station between 2013-08-06 at 10:00 and 2013-08-07 at 13:00. It involved a Carlo Gavazzi EM20 power analyzer [28] and the VFD internal energy meter. As mentioned in its datasheet, the accuracy of the power analyzer is ± 5%. Because Sigtuna station utilizes the same devices as the ones in the STR station, it can be assumed that the error calculated in table 18 can be used for that case too.

<table>
<thead>
<tr>
<th>Method</th>
<th>VFD internal energy meter</th>
<th>Carlo Gavazzi power analyzer</th>
<th>VFD internal energy meter</th>
<th>Carlo Gavazzi power analyzer</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Pump</td>
<td>Pump 1</td>
<td>Pump 2</td>
<td>Pump 2</td>
</tr>
<tr>
<td>2013-08-06 at 10:00</td>
<td>1720.10</td>
<td>592.00</td>
<td>1623.20</td>
<td>431.70</td>
</tr>
<tr>
<td>2013-08-07 at 13:00</td>
<td>1726.40</td>
<td>598.50</td>
<td>1632.20</td>
<td>440.40</td>
</tr>
<tr>
<td>Results [kWh]</td>
<td>6.30</td>
<td>6.50</td>
<td>9.00</td>
<td>8.70</td>
</tr>
<tr>
<td>Results with 3% losses [kWh]</td>
<td>6.30</td>
<td>6.70</td>
<td>9.00</td>
<td>8.96</td>
</tr>
<tr>
<td>Error [%]</td>
<td>3.07</td>
<td>-3.44</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Error with 3% losses [%]</td>
<td>5.97</td>
<td>-0.33</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The difference in values is due to the losses that occur because of the VFD use (assumed to be 3% of the input power), the accuracy of each device and the fact that the power analyzer is installed before the VFD, as seen in figure 49. If 3% is added to the value recorded by the Carlo Gavazzi power analyzer, pump 1 has an energy use of 6.70 kWh and for pump 2 energy usage becomes 8.97 kWh.

![Figure 49: VFD and power analyzer installation](image)
5.4 Results of comparison between methods

Table 19 shows what the difference in percentage between DOL and VFD control is for each of the four methods. For the STR station, with the first three methods, the lowest specific energy was found for an optimal frequency of 30 Hz and for the last method was measured at 31 Hz. For Sigtuna, optimal frequency was calculated in theory to be at 32 Hz, was measured with HIL at 32 Hz and in the field as being 34 Hz. As can be seen in the table below, there is a noticeable difference between calculated and measured results.

<table>
<thead>
<tr>
<th></th>
<th>Sigtuna station</th>
<th>STR station</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Optimal frequency [Hz]</td>
<td>Total Savings [%]</td>
</tr>
<tr>
<td></td>
<td>DOL</td>
<td>VFD</td>
</tr>
<tr>
<td>Theoretical calculation</td>
<td>50</td>
<td>32</td>
</tr>
<tr>
<td>Simplified theoretical tool</td>
<td>50</td>
<td>32</td>
</tr>
<tr>
<td>Hardware in the loop (HIL)</td>
<td>50</td>
<td>34</td>
</tr>
<tr>
<td>Measured data</td>
<td>50</td>
<td>34</td>
</tr>
</tbody>
</table>

Each of the two parameters that are used in the $E_{sp}$ calculation algorithm are susceptible to errors. To see what the values for the total minimum and maximum error for each case is, which are calculated based on figure 50, it is necessary to create a best and a worst case scenario for each pump station, which can sum up all errors.

Firstly, by taking into account, from chapter 5.3.2, the measured error between a power analyzer and VFD energy meter, the minimum and maximum values that the energy can have were calculated. Secondly, a ±1% error to the water level values was applied, which is due to level sensor accuracy. After that, the starting and running conditions of both pump stations were simulated with the “Test Generation” tool, as it can be seen in the attachment. In that way, it could be seen that the $E_{sp}$ algorithm does not add any kind of error when calculating the energy but, depending on each case, adds different values of error to the volume calculation part. Finally, specific energy is calculated for best and worst case scenarios:

- **Best case**: Difference in percent between the minimum value of specific energy for VFD control and the maximum value of specific energy use for DOL control
- **Worst case**: Difference in percent between the maximum value of specific energy for VFD control and the minimum value of specific energy use for DOL control
For the STR station, it is assumed that data was logged every 60 seconds, and the pump flow was linearly dependent on the head. Two cases were created: one using a constant inflow of 3.5 l/s (best case scenario), and the second using inflow values between 3 l/s and 4 l/s with change every 10 seconds (worst case scenario). The discrepancy between actual volume and volume calculated by the Esp algorithm was found to be between 2.49% and 3.77%. By having all the necessary information, the total savings in the best and worst case scenario were calculated, as seen in table 20.

Table 20: Best and worst case scenario for measured data – STR

<table>
<thead>
<tr>
<th></th>
<th>VFD control method</th>
<th>DOL control method</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Energy [kWh]</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>-0.33%</td>
<td>+5.97%</td>
</tr>
<tr>
<td></td>
<td>6.67</td>
<td>6.70</td>
</tr>
<tr>
<td></td>
<td>7.09</td>
<td>7.09</td>
</tr>
<tr>
<td></td>
<td>24.07</td>
<td>24.15</td>
</tr>
<tr>
<td></td>
<td>25.59</td>
<td>25.59</td>
</tr>
<tr>
<td><strong>Water level [m]</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>-1%</td>
<td>+1%</td>
</tr>
<tr>
<td></td>
<td>60.69</td>
<td>61.31</td>
</tr>
<tr>
<td></td>
<td>61.92</td>
<td>61.92</td>
</tr>
<tr>
<td></td>
<td>171.19</td>
<td>172.92</td>
</tr>
<tr>
<td></td>
<td>174.64</td>
<td>174.64</td>
</tr>
<tr>
<td><strong>Volume [m³]</strong></td>
<td>+2.49%</td>
<td>+3.77%</td>
</tr>
<tr>
<td></td>
<td>125.02</td>
<td>123.25</td>
</tr>
<tr>
<td></td>
<td>129.15</td>
<td>129.15</td>
</tr>
<tr>
<td></td>
<td>352.65</td>
<td>347.58</td>
</tr>
<tr>
<td></td>
<td>364.26</td>
<td>364.26</td>
</tr>
<tr>
<td><strong>Esp [kWh/m³]</strong></td>
<td>Minimum: 0.0516</td>
<td>Minimum: 0.0660</td>
</tr>
<tr>
<td></td>
<td><strong>Actual case: 0.0543</strong></td>
<td><strong>Actual case: 0.0694</strong></td>
</tr>
<tr>
<td></td>
<td>Maximum: 0.0567</td>
<td>Maximum: 0.0725</td>
</tr>
<tr>
<td><strong>Savings [%]</strong></td>
<td>Worst case: 14.09</td>
<td>Actual case: 21.75</td>
</tr>
<tr>
<td></td>
<td>Actual case: 21.75</td>
<td><strong>Best case: 28.82</strong></td>
</tr>
</tbody>
</table>

Figure 50: Total error due to calculation methods and accuracy of instrumentation
For Sigtuna municipal station, it is assumed that data was logged every 60 seconds, and the pump flow was linearly dependent on the head. Two cases were created: first one uses a constant inflow of 2.3 l/s (best case scenario), second one using inflow between 1 l/s and 3 l/s with change every 10 seconds (worst case scenario). The discrepancy between actual volume and volume calculated by the \( E_{sp} \) algorithm was found to be between 0.68% and 1.61%. The same method as in the laboratory station was used, resulting in Table 21.

### Table 21: Best and worst case scenario for measured data – Sigtuna

<table>
<thead>
<tr>
<th></th>
<th>VFD control method</th>
<th>DOL control method</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Energy [kWh]</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>-0.33%  ( E_{sp} ) algorithm</td>
<td>+5.97%</td>
<td>-0.33%  ( E_{sp} ) algorithm</td>
</tr>
<tr>
<td>20.58</td>
<td>20.66</td>
<td>21.89</td>
</tr>
<tr>
<td><strong>Water level [m]</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>-1%  ( E_{sp} ) algorithm</td>
<td>+1%</td>
<td>-1%  ( E_{sp} ) algorithm</td>
</tr>
<tr>
<td>83.54</td>
<td>84.39</td>
<td>85.23</td>
</tr>
<tr>
<td><strong>Volume [m³]</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>+0.68%  ( E_{sp} ) algorithm</td>
<td>+1.61%</td>
<td>+0.68%  ( E_{sp} ) algorithm</td>
</tr>
<tr>
<td>213.63</td>
<td>214.37</td>
<td>219.96</td>
</tr>
<tr>
<td><strong>( E_{sp} ) [kWh/m³]</strong></td>
<td>Minimum: 0.0935</td>
<td>Minimum: 0.0961</td>
</tr>
<tr>
<td></td>
<td><strong>Actual case: 0.0961</strong></td>
<td><strong>Actual case: 0.1083</strong></td>
</tr>
<tr>
<td></td>
<td>Maximum: 0.1024</td>
<td>Maximum: 0.1151</td>
</tr>
<tr>
<td><strong>Savings [%]</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Worst case: 2.56</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Actual case: 11.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Best case: 18.76</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

After analyzing the results from chapter 5, some remarks can be made:

The values obtained with theoretical and simplified theoretical models are for an ideal case, when it is supposed that a pump knows from the beginning what the optimal frequency for the lowest specific energy is and the motor runs all the time at that fixed speed.

When using HIL tool to run the controllers, it can be seen that the difference between theoretic and HIL savings is smaller than the difference between theoretic and measured values. This is due to a fully controlled environment (input parameters keep the value that is set and no other external factors influence the running of the VFDs, like in a real case scenario).
In reality, VFDs have other complementary functions that are using additional electricity. A pump motor has a start time when its speed increases from zero to the frequency of the grid and then decreases to the optimal value, also contributing to a higher amount of electricity. The opposite thing happens before the pump stops.

For cases where there is a rapid variation of inflow or an overflow in a pump station, $E_{sp}$ algorithm does not give very accurate results, so the water level should first be checked before starting to calculate. To eliminate all the problems caused by a short water rise time or pumping cycle time, the logging device should have the option to record samples every second. In this way, a more precise result of the volume will be given and no errors will disrupt the algorithm’s calculation.

As seen in table 19 and also in figure 52, there is no intersection between the ranges of calculated specific energy corresponding to each control method, meaning that for all cases VFD control always uses less electricity than DOL control.

For the STR case, the optimal frequency matches for both theoretical cases and HIL (30Hz) and differs for the last method (31 Hz), which can be explained by the variation of the inflow when measuring data (for this case inflow had a small increase). In Sigtuna, measured data has shown a corresponding value of 34 Hz for the frequency, different than the other three methods, which found a result of 32 Hz. The discrepancy between theoretic calculation and measured data (32 Hz vs. 34 Hz) is justified by the fact that for both cases specific energy has very similar values.

In Sigtuna, one reason for the small amount of savings is that there is a very short pumping cycle (around 1 to 2 minutes) and the period of running on the optimal frequency has a small impact on the result. Going to the site and doing measurements of power and flow, as seen in appendix 5, show that there is a greater savings potential, around 37.5%. A solution that will increase energy savings without doing any modifications to the equipment is to increase the pump start and stop levels, leading to a decrease of the static head, thus having more friction losses throughout the piping system, which will be reduced by introducing a VFD.
6. Conclusion

As it is shown in figure 51, initial assumption about the accuracy of each evaluation method was wrong. For the same frequency, all the methods give very similar values of specific energy. Their ease of use was quantified by the number of calculation steps and the period of time it took for each method to be conducted. The complexity of the use increases when real instrumentation is introduced (logging devices, VFDs, etc.), like in the case of HIL and measured data.

Moreover, VS is seen as a good way of saving energy. By having in mind measured values of the specific energy from tables 10 and 11 and figure 52, it can be seen that VFD control always has lower results than DOL control. In the right applications, savings due to VFD control can reach 50%, when compared to DOL [34].
7. Further research

The next step is to use the evaluation methods during longer periods of time and on a wider range of pump stations and document how much energy is saved when DOL control is replaced with VFD control.

The result given by the simplified model has to be closer to real measurements, so the efficiencies of the impeller, motor and VFD need to be rethought based on more measured data from pump stations.

By creating a more user-friendly interface for the HIL tool, it can be used as a good instrument for showing energy savings in a controlled environment, without any external interference.

The $E_{sp}$ algorithm can be optimized by using additional filtering functions and a logging device that can save water level data every second, instead of every 60 seconds. Also, the accuracy of the measuring devices can be improved by replacing them with some that are more technologically advanced.

The sensitivity analysis can include more simulated scenarios and a better approximation of the pump outflow.
8. References


9. Appendix

Appendix 1: VFD control – Sigtuna output

![Water Level Graph](image)

![Pump Operating Frequency Graph](image)

![Average Frequency per Day for Each Pump](image)
Appendix 2: DOL control – Sigtuna output
Appendix 3: Pump performance curves in STR station

Table 22: Pump performance curves - STR

<table>
<thead>
<tr>
<th>Pump</th>
<th>N 3102 SH 3~ 2p</th>
</tr>
</thead>
<tbody>
<tr>
<td>Motor</td>
<td>N3102.181 18-10-2AL-W 4.2KW</td>
</tr>
<tr>
<td>Impeller</td>
<td>255 152mm</td>
</tr>
<tr>
<td>Flow [l/s]</td>
<td>Head [m]</td>
</tr>
<tr>
<td>0.0028061</td>
<td>31.947</td>
</tr>
<tr>
<td>1.0335</td>
<td>30.773</td>
</tr>
<tr>
<td>4.1257</td>
<td>27.459</td>
</tr>
<tr>
<td>5.1564</td>
<td>26.443</td>
</tr>
<tr>
<td>6.1871</td>
<td>25.469</td>
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<tr>
<td>8.2486</td>
<td>23.636</td>
</tr>
<tr>
<td>9.2793</td>
<td>22.764</td>
</tr>
<tr>
<td>10.31</td>
<td>21.911</td>
</tr>
<tr>
<td>11.341</td>
<td>21.067</td>
</tr>
<tr>
<td>12.371</td>
<td>20.222</td>
</tr>
<tr>
<td>13.402</td>
<td>19.366</td>
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<tr>
<td>14.433</td>
<td>18.488</td>
</tr>
<tr>
<td>15.464</td>
<td>17.581</td>
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<tr>
<td>16.494</td>
<td>16.639</td>
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<tr>
<td>17.525</td>
<td>15.659</td>
</tr>
<tr>
<td>18.556</td>
<td>14.642</td>
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<tr>
<td>20.617</td>
<td>12.509</td>
</tr>
<tr>
<td>22.679</td>
<td>10.277</td>
</tr>
<tr>
<td>23.709</td>
<td>9.1334</td>
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</table>
Appendix 4: Pump performance curves in Sigtuna station

Table 23: Theoretical specific energy values for different frequencies - STR

<table>
<thead>
<tr>
<th>Frequency</th>
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<th>49</th>
<th>48</th>
<th>47</th>
<th>46</th>
<th>45</th>
<th>44</th>
<th>43</th>
<th>42</th>
<th>41</th>
<th>40</th>
<th>39</th>
<th>38</th>
<th>37</th>
<th>36</th>
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<th>34</th>
<th>33</th>
<th>32</th>
<th>31</th>
<th>30</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flow</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>7</td>
<td>8</td>
<td>9</td>
<td>10</td>
<td>11</td>
<td>12</td>
<td>13</td>
<td>14</td>
<td>15</td>
<td>16</td>
<td>17</td>
<td>18</td>
<td>19</td>
<td>20</td>
<td>21</td>
<td>22</td>
</tr>
<tr>
<td>Head</td>
<td>12,7</td>
<td>12,2</td>
<td>11,7</td>
<td>11,2</td>
<td>10,8</td>
<td>10,3</td>
<td>9,9</td>
<td>9,5</td>
<td>9,1</td>
<td>8,8</td>
<td>8,4</td>
<td>8,0</td>
<td>7,6</td>
<td>7,2</td>
<td>6,9</td>
<td>6,6</td>
<td>6,3</td>
<td>6,0</td>
<td>5,7</td>
<td>5,4</td>
<td>5,1</td>
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<tr>
<td>Efficiency</td>
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<td>50,2</td>
<td>50,1</td>
<td>50,0</td>
<td>49,9</td>
<td>49,8</td>
<td>49,7</td>
<td>49,6</td>
<td>49,5</td>
<td>49,4</td>
<td>49,3</td>
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<td>48,7</td>
<td>48,6</td>
<td>48,5</td>
<td>48,4</td>
<td>48,3</td>
</tr>
<tr>
<td>Input power</td>
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<td>4.77</td>
<td>4.50</td>
<td>4.23</td>
<td>3.96</td>
<td>3.69</td>
<td>3.42</td>
<td>3.15</td>
<td>2.88</td>
<td>2.61</td>
<td>2.34</td>
<td>2.07</td>
<td>1.80</td>
<td>1.53</td>
<td>1.26</td>
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<td>0.45</td>
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<td>0.01</td>
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</table>

Table 24: Pump performance curves - Sigtuna

<table>
<thead>
<tr>
<th>Pump</th>
<th>N 3153 HT 3-4p</th>
</tr>
</thead>
<tbody>
<tr>
<td>Impeller</td>
<td>450 289mm</td>
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</table>

<table>
<thead>
<tr>
<th>Flow [l/s]</th>
<th>Head [m]</th>
<th>Shaft power P2 [kW]</th>
<th>Power input P1 [kW]</th>
<th>Efficiency [%]</th>
<th>Total efficiency [%]</th>
<th>NPSH-values [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0028144</td>
<td>34,388</td>
<td>6.9854</td>
<td>7.8799</td>
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<td>4,1637</td>
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<tr>
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<td>33,623</td>
<td>7.1178</td>
<td>8.0274</td>
<td>10,775</td>
<td>9.5516</td>
<td>4,0182</td>
</tr>
<tr>
<td>4.5478</td>
<td>32,873</td>
<td>7.2607</td>
<td>8.187</td>
<td>20,49</td>
<td>18,158</td>
<td>3,8875</td>
</tr>
<tr>
<td>6.8202</td>
<td>32,14</td>
<td>7.4279</td>
<td>8.3742</td>
<td>29,075</td>
<td>25,785</td>
<td>3,7731</td>
</tr>
<tr>
<td>11.365</td>
<td>30,746</td>
<td>7.8719</td>
<td>8.8735</td>
<td>43,297</td>
<td>38,404</td>
<td>3,5887</td>
</tr>
<tr>
<td>13.638</td>
<td>30,084</td>
<td>8.1504</td>
<td>9.1866</td>
<td>49,096</td>
<td>43,543</td>
<td>3,5137</td>
</tr>
<tr>
<td>15.91</td>
<td>29,443</td>
<td>8.4581</td>
<td>9.5382</td>
<td>54,131</td>
<td>47,995</td>
<td>3,4461</td>
</tr>
<tr>
<td>18.183</td>
<td>28,818</td>
<td>8.7836</td>
<td>9.9102</td>
<td>58,479</td>
<td>51,824</td>
<td>3,3835</td>
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<tr>
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<td>28,023</td>
<td>9.1155</td>
<td>10,292</td>
<td>62,207</td>
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<tr>
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<td>27,59</td>
<td>9.4434</td>
<td>10,671</td>
<td>65,30</td>
<td>57,852</td>
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<td>25</td>
<td>26,974</td>
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<td>11,04</td>
<td>68,050</td>
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<td>26,349</td>
<td>10,064</td>
<td>11,395</td>
<td>70,278</td>
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<td>3,1691</td>
</tr>
<tr>
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<td>10,353</td>
<td>11,737</td>
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<tr>
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<td>10,634</td>
<td>12,071</td>
<td>73,521</td>
<td>64,767</td>
<td>3,1107</td>
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<tr>
<td>34.09</td>
<td>24,398</td>
<td>10,913</td>
<td>12,403</td>
<td>74,598</td>
<td>65,629</td>
<td>3,1077</td>
</tr>
</tbody>
</table>
### Table 25: Theoretical specific energy values for different frequencies - Sigtuna

<table>
<thead>
<tr>
<th>Frequency [Hz]</th>
<th>Start level [m]</th>
<th>Stop level [m]</th>
<th>Rising time [s]</th>
<th>Pumping time [s]</th>
<th>Flow meter (instantaneous value) [l/s]</th>
<th>Power VFD [kW]</th>
<th>( E_{sp} ) [kWh/m³]</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>0.4</td>
<td>0.5</td>
<td>100</td>
<td>9</td>
<td>34.34</td>
<td>13.4</td>
<td>0.108393192</td>
</tr>
<tr>
<td>45</td>
<td>0.4</td>
<td>0.5</td>
<td>93</td>
<td>9.8</td>
<td>28.7</td>
<td>9.58</td>
<td>0.092721642</td>
</tr>
<tr>
<td>40</td>
<td>0.4</td>
<td>0.5</td>
<td>96</td>
<td>12.7</td>
<td>23.08</td>
<td>6.54</td>
<td>0.078711727</td>
</tr>
<tr>
<td>35</td>
<td>0.4</td>
<td>0.5</td>
<td>118</td>
<td>17.4</td>
<td>17.47</td>
<td>4.17</td>
<td>0.06630414</td>
</tr>
<tr>
<td>30</td>
<td>0.4</td>
<td>0.5</td>
<td>105</td>
<td>35.86</td>
<td>9.64</td>
<td>2.46</td>
<td>0.070885201</td>
</tr>
<tr>
<td>26</td>
<td>0.4</td>
<td>0.5</td>
<td>-</td>
<td>-</td>
<td>0.34</td>
<td>1.32</td>
<td>-</td>
</tr>
</tbody>
</table>

### Appendix 5: Specific energy curve in Sigtuna station

Table 26: Measured specific energy values for different frequencies - Sigtuna

<table>
<thead>
<tr>
<th>Frequency [Hz]</th>
<th>Start level [m]</th>
<th>Stop level [m]</th>
<th>Rising time [s]</th>
<th>Pumping time [s]</th>
<th>Flow meter (instantaneous value) [l/s]</th>
<th>Power VFD [kW]</th>
<th>( E_{sp} ) [kWh/m³]</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>0.4</td>
<td>0.5</td>
<td>100</td>
<td>9</td>
<td>34.34</td>
<td>13.4</td>
<td>0.108393192</td>
</tr>
<tr>
<td>45</td>
<td>0.4</td>
<td>0.5</td>
<td>93</td>
<td>9.8</td>
<td>28.7</td>
<td>9.58</td>
<td>0.092721642</td>
</tr>
<tr>
<td>40</td>
<td>0.4</td>
<td>0.5</td>
<td>96</td>
<td>12.7</td>
<td>23.08</td>
<td>6.54</td>
<td>0.078711727</td>
</tr>
<tr>
<td>35</td>
<td>0.4</td>
<td>0.5</td>
<td>118</td>
<td>17.4</td>
<td>17.47</td>
<td>4.17</td>
<td>0.06630414</td>
</tr>
<tr>
<td>30</td>
<td>0.4</td>
<td>0.5</td>
<td>105</td>
<td>35.86</td>
<td>9.64</td>
<td>2.46</td>
<td>0.070885201</td>
</tr>
<tr>
<td>26</td>
<td>0.4</td>
<td>0.5</td>
<td>-</td>
<td>-</td>
<td>0.34</td>
<td>1.32</td>
<td>-</td>
</tr>
</tbody>
</table>
Figure 53: Measured specific energy curve – Sigtuna