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Combined Electricity and Hydraulic Analysis of Cascade Heating Supply Infrastructure with EA-PSM Software

dr. Vytautas Šiožinys[1], dr. Milvydas Šiožinys[1], Mantas Kaminickas[1], Martynas Jonaitis[2], Arūnas Rimkus[2],
[1]*Senior engineer*
[2]*Junior engineer*
UAB EnergyAdvice K. Baršausko g. 59 LT-51423 Kaunas, Lithuania
www.energyadvice.lt/en
info@energyadvice.lt

***Abstract*—Hydraulic pumps operation point control is essential part of any heating supply infrastructure which vastly influences the performance and effectiveness of the network. The optimization of pumps operating points is time consuming and calculation heavy work. It is a common practise to simplify this tasks by increasing the reserve threshold for the pumps parameters and skip the system multiple operation point analysis. All this streamlining leads to the low-efficiency performance of the network which increase both initial building and exploitation costs. Today's constantly increasing scope and flexibility of both electric and hydraulic system modelling software allows engineers to perform the full in-depth network analysis which can be used to both increase performance and reduce the losses of the heating supply infrastructure.**

I. INTRODUCTION

In today's world with the ever-growing market it is very important to assure the optimization and effectiveness of processes in any branch of industry. Effectiveness has influence upon the costs - if the effectiveness lowers, costs of product/service rise, which then create a general rise of prices. In such case, company cannot reach the optimal economic potential, therefore it slows the growth of the company, halts investments and customers. Essentially, the added costs are paid by the customer and his satisfaction with the supplier decreases.

It is very difficult to analyze the technology process as a single object, therefore it is important to separate the process into general, more basic energetic factors. Having this information allows us to concentrate on the different parts of the process and constitute them further if needed. The result of said method is a "tree" of an energetic process called Sankey diagram. Seeing the main energy-required processes and finding solutions to optimization become very easy once the Sankey diagram is drawn. It is important to note that the main parts of the process should be accounted for optimization, as optimizing small parts will not have a big impact on the total effectiveness.

Heating and hot water supply is one the branches in which optimization of process effectiveness is a must. This branch is very developed as it can be found not only in municipal households, but also in industry. To further analyze this branch, we will examine heating system study of a town district, which was done using power and hydraulic system modeling program EA-PSM[1].

II. SYSTEM PARAMETERS AND PRESUMPTIONS[10],[11]

The system in the study is composed a network of pipes and a pumping station, in which 4 parallel circulation pumps run simultaneously. The individual houses, which are supplied with water are situated in flat terrain, on an incline, on a hill, whereas the pump station is at the foot of the hill, by the edge of the field. There is a 30 m height difference between the pump station and the top of the hill.

While designing heat transfer network, an engineer must face environmental and other factors, which cannot be alternated or changed:

1. Surface terrain (hills and plains). Hydraulic pumps that should be used for the application directly depends on the altitude difference between the highest and the lowest point. This difference in this article will be referenced as the height difference. With bigger height difference, the flexibility of grid considerably decreases since pump operation point range is limited. Control options are also limited, since decreasing pump speed will lead to less flow of the heating water and minimal pressure requirement will not be met;
2. Total length of the pipe grid. This parameter purely depends on the consumer geographical location. Length of the grid and nominal pipe diameter dictates the system hydraulic resistance and this resistance changes system hydraulic characteristic. Decreasing grid resistance leads to higher flow of the heating water and lesser energy losses. Since length of the pipeline is constant parameter, system characteristic can be alternated during design stages by changing nominal pipe diameter;
3. Lowest and highest demand rates depending on the season (summer or winter). The system must work at both demand rates. If it is not possible to control the pumps, it might be difficult to assure that the same pumps will fulfil

the demand. In such case, the solution would be to build a pump station with series of both parallel and consecutive pumps, so that different branches would supply the extra demand. The average pump effectiveness of an operating zone is from 15 to 70 %, thus if the pump is too powerful, too weak or if the pump has the wrong operating point there will be a significant drop of the system effectiveness;

4. Minimal pressure. The system must guarantee minimal pressure to every consumer. However, by raising the pressure over the minimal value, the system induces energy loss due to friction in piping. For this reason, it is advised to have a controlled system for raising or lowering pressure depending on various situations;

Whilst conducting the study, we assume that the minimal pressure in every node must not be lower than in the given formula (1).

$$H_{\min} = \left(H_z + H_{1atm}\right) \cdot SF \tag{1}$$

where H_z is the geographical height of the node, meters, H_{1atm} is the atmospheric pressure of the water column, meters, SF is the safety factor of pressure, which is 1.3 (30%). The safety factor is added so that in case of an emergency, the pressure of the system would not drop below the minimal pressure.

We also assume that the minimal pressure must be ensured only at the local connections to buildings. For heating water to reach the whole building locally installed circulation pumps are required.

It is unknown what the ratio between the summer-low and winter-high demand of heating water states are. It purely depends on the difference of the temperatures, which changes every season. To determine the value of this ratio, Lithuania cities and towns analysis of heat consumption[5][6] in the hottest and coldest months of May and January over the period of 3 years were analyzed. Ratio is calculated[9] by dividing sums of heat consumption in buildings at months in different seasons. The size of the town or city did not influence the ratio and it calculations shown that it varies between 4 to 6.

The system analyzed in our study is made of a closed pipe contour and two pump stations in which up to 4 parallel hot water circulator pumps work simultaneously. Pumps used first pump station are Grundfos TP 100-1410/2 A3-F-O-DAQF and in the second pump station Grundfos TP 150-660/4 A-F-A-BAQE. Municipal buildings are located on a field, on a slope and on a hill. The first pump station is at the edge of the field, whereas the second pump station is at the top of the hill, the height difference between both pump stations is 50 m. The electric power system is also analyzed in this study: pump stations are connected to a 10 kV system, which is 500 m. away from the pump station with a transformer station between them. The pumps are connected through variable frequency drives which depending on the current hydraulic state change operation point of pumps. The principle scheme of the network is shown in Figure 1 and corresponding EA-PSM one-line network is depicted in Figure 2.

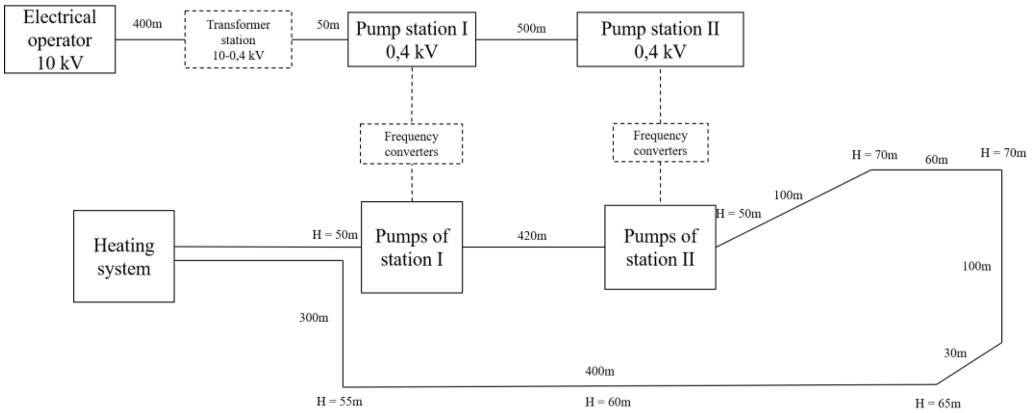

Figure 1. Principle scheme of analysed heating network

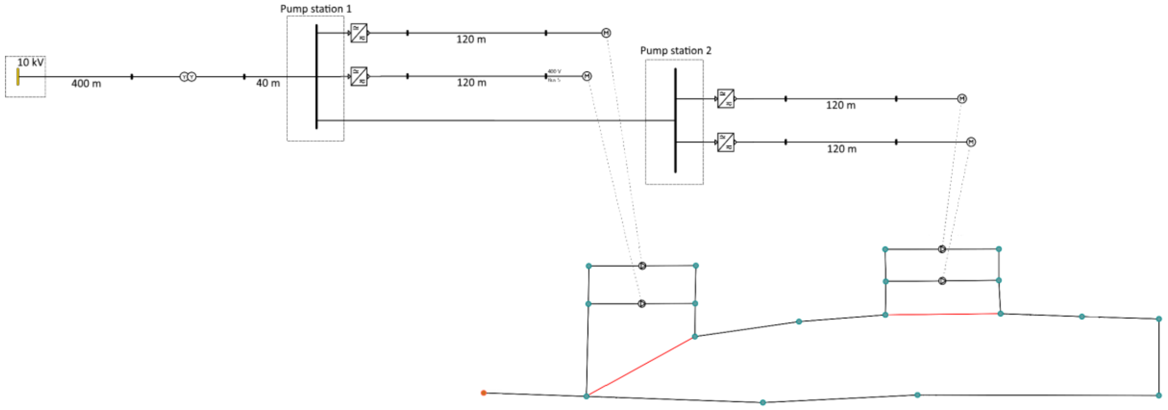

Figure 2. Principle scheme of analysed system in the EA-PSM environment

III. ANALYSIS METHOD

During this study all calculations and analysis was performed using EA-PSM power and hydraulic system modelling software. To analyze the district heating network both electric and hydraulic grids are modelled.

A. *Electric grid analysis*

Electric network model consists of power transmission equipment and electric motors. Electrical motor RPM depends on the VFD output frequency and affects the linked hydraulic pump characteristic. Motor mechanical load depends on the calculated hydraulic pump operating point. To evaluate voltage drops and identify the energetic components of the electrical network (losses in the conducting equipment and consumed motor power) simple power flow calculation was performed.

B. *Hydraulic grid analysis*

Hydraulic network model consists piping system, nodes and hydraulic pumps. The heights of analyzed heating system locations are registered on the corresponding EA-PSM software hydraulic nodes. Hydraulic pumps operation point depends on the linked electric motor. To evaluate the pressure drops and energic components of the hydraulic network hydraulic load flow calculation was performed.

Software main hydraulic calculation algorithms are programmed using Newton-Rapson iterative method and are based on the equations described in following paragraphs.

1) *General equations*[1],[3]

The pressure loss in a pipe, tube or duct can be calculated with the *Darcy-Weisbach equation*.

$$\Delta p = \lambda \cdot \frac{l}{d_h} \tag{2}$$

where, Δp - pressure loss (Pa), λ - Darcy-Weisbach friction coefficient, l - length of duct or pipe (m), v - velocity (m/s), d_h - hydraulic diameter (m), ρ - density (kg/m^3).

The *Darcy-Weisbach equation* is valid for fully developed, steady state and incompressible flow. The friction factor or coefficient - λ - depend on the flow, if it is laminar, transient or turbulent (the Reynolds Number) - and the roughness of the tube or duct.

The friction coefficients used when calculating resistance or pressure loss (or major loss) in ducts, tubes or pipes can be calculated with the *Colebrook equation*:

$$\frac{1}{\lambda^{1/2}} = -2\log\left(\frac{2.51}{\mathrm{Re}\cdot\lambda^{1/2}} + \frac{k/d_h}{3.72}\right) \tag{3}$$

where, λ - Darcy-Weisbach friction coefficient, *Re* - Reynolds Number, *k* - roughness of duct, pipe or tube surface *(m, ft)*, d_h - hydraulic diameter *(m, ft)*.

The Colebrook equation is only valid at turbulent flow conditions. The Colebrook equation is generic and can be used to calculate friction coefficients for different kinds of fluid flows - like air ventilation ducts, pipes and tubes with water or oil, compressed air and much more.

Absolute viscosity - coefficient of absolute viscosity - is a measure of internal resistance. Dynamic (absolute) viscosity is the tangential force per unit area required to move one horizontal plane with respect to another plane - at unit velocity - when maintaining unit distance apart in the fluid.

Kinematic viscosity is the ratio of - absolute (or dynamic) viscosity to density - a quantity in which no force is involved. Kinematic viscosity can be obtained by dividing the absolute viscosity of a fluid with the fluid mass density:

$$\nu = \frac{\mu}{\rho} \tag{4}$$

where ν - kinematic viscosity(m^2/s), μ - absolute or dynamic viscosity(Ns/m^2), ρ – density(kg/m^3).

Reynolds number can be calculated using following equation:

$$\mathrm{Re} = \frac{QD}{\nu A} \tag{5}$$

where Q - the volumetric flow rate (m^3/s), D – pipe inside diameter (m), *v* – kinematic viscosity (m^2/s), A - is the pipe's cross-sectional area (m^2).

2) *Affinity law*[4]

Since hydraulic network uses variable frequency drives to regulate operation point of the hydraulic pumps, nominal pump characteristics (at nominal electric motor rotation speed) must be recalculated to reduced or increased output frequencies. To perform this modelling *affinity law* (also known as “pump law”) was used. This law is described (6), (7) and (8) equations.

Volume capacity of a centrifugal pump can be expressed like:

$$\frac{q_1}{q_2} = \left(\frac{n_1}{n_2}\right)\cdot\left(\frac{d_1}{d_2}\right) \tag{6}$$

where q - volume flow capacity (m^3/s), n – revolutions per minute (rpm), d - shaft diameter (m).

The head or pressure of a centrifugal pump can be expressed like:

$$\frac{dp_1}{dp_2} = \left(\frac{n_1}{n_2}\right)^2\cdot\left(\frac{d_1}{d_2}\right)^2 \tag{7}$$

where dp - head or pressure (m).

The power consumption of a centrifugal pump can be expressed as

$$\frac{P_1}{P_2} = \left(\frac{n_1}{n_2}\right)^3\cdot\left(\frac{d_1}{d_2}\right)^3 \tag{8}$$

where P – electrical power (W).

Affinity law states, that the ratio of the given parameters always stays the same. Nominal ratios are calculated and then are used for recalculating pump characteristic at different electric motor rotation speed or another changed parameter.

3) *Pump efficiency*[1]

Hydraulic pump efficiency is purely depended on the pump characteristic, which varies with different pump models. Since the pump characteristic depends on pump motor rotation speed (in this case VFD ouput frequency) the efficiency of the pump is calculated after the affinity law is already applied.

IV. CASE AA

This case represents the maximum heating energy consumption in the winter season. Pump characteristics with sufficient nominal flow are chosen so that the water flow could be lowered during the summer season. The pumps also have to ensure minimal pressure conditions, therefore, two pump stations are designed. First station is located at the base of the field. The pumps at this station are chosen with a wide range of flow regulation, but with limited ability to create high pressure, to prevent unnecessary overpressure. The second pump station is located at the foot of the hill. Pumps for this station are chosen to compensate the hill height difference. At each station pumps are connected in a parallel to ensure system flow control flexibility and increase the credibility.

Firstly, the hydraulic flows calculation was performed and Sankey diagram was drawn (Figure 3). The diameter of piping was iterated until the predefined conditions were met. It was determined that pipe optimal diameter is DN200 XXS.

With these conditions, the flow of water in the system is 475 m^3/h. Almost 35% of the power from the electricity provider is lost in various parts of the system: the most extensive losses are caused by the VFDs and the pump COPs. The remaining energy is consumed in the hydraulic network: one part is losses in piping and the remaining is used for heating work at the consumers.

TABLE 1. CASE AA PUMP OPERATING POINTS SUMMARY

Title	Manufacturer	Model	η, %	P, kW	Q, m^3/s	dH, m
Pump station I pumps	Grundfos	TP 150-660/4 A-F-A-BAQE - 98858121	81.374	23.747	0.066	29.3
Pump station II pump	Grundfos	TP 100-1410/2 A3-F-O-DAQF - 99088540	77.447	58.493	0.066	68.563

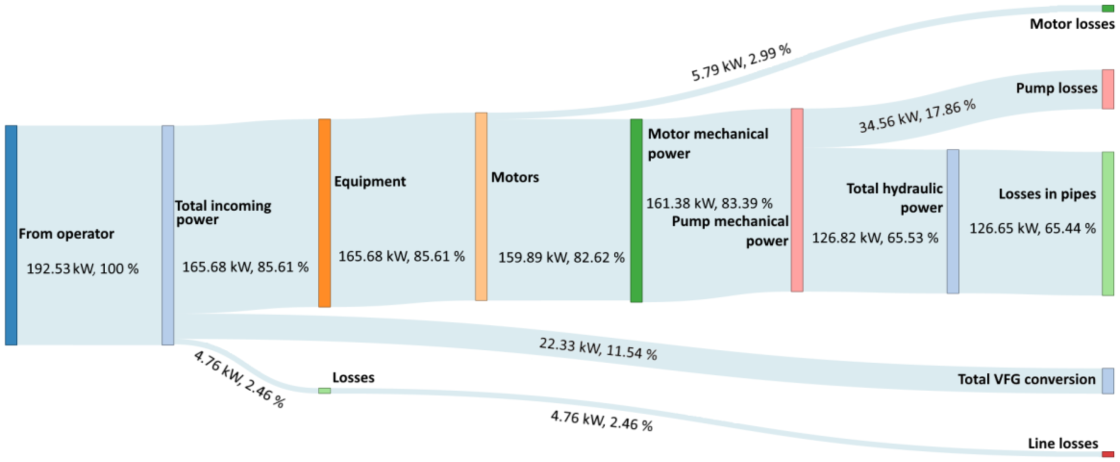

Figure 3. Sankey diagram for the AA case

TABLE 2. CONDITION AA PUMP EFFECTIVENESS

Title	Manufacturer	Model	η, %	η_{max}, %	PR, %	RPM
Pump station I pumps	Grundfos	TP 150-660/4 A-F-A-BAQE - 98858121	81.37	81.4	99	2087
Pump station II pumps	Grundfos	TP 100-1410/2 A3-F-O-DAQF - 99088540	77.447	77.5	99	2186

The performance ratio (PR) is a term used to describe the pump operation point effectiveness. PR is a ratio between COP and the maximum available effectiveness in percent. The purpose of this ratio is to show how effectively the pumps operating energetically. PR ratio of pumps which are operating under AA condition parameters is shown in Table 2.

V. CASE BB

The goal of this case is to further analyze the results of case AA to identify whether minimal piping diameter is the most effective. In case BB the piping diameter was reduced to DN250 SCH160.

By lowering the resistance of the hydraulic system and changing pumps operating point, it was not possible to reach the required flow and maintain the minimal pressure condition since the hydraulic system characteristic is not linear. Having a pipe system with smaller resistance meant that the revolutions of pump electrical motors were lowered by 18%, whereas the flow increased to 541 m^3/h. To make the flow in both(AA and BB) conditions equal, a different combination of pumps is required. Sankey diagram (Figure 4) indicates that a higher flow of water does not have an impact on total consumed electrical energy, neither does it raise the hydraulic losses, which means that system with case BB parameters is more effective.

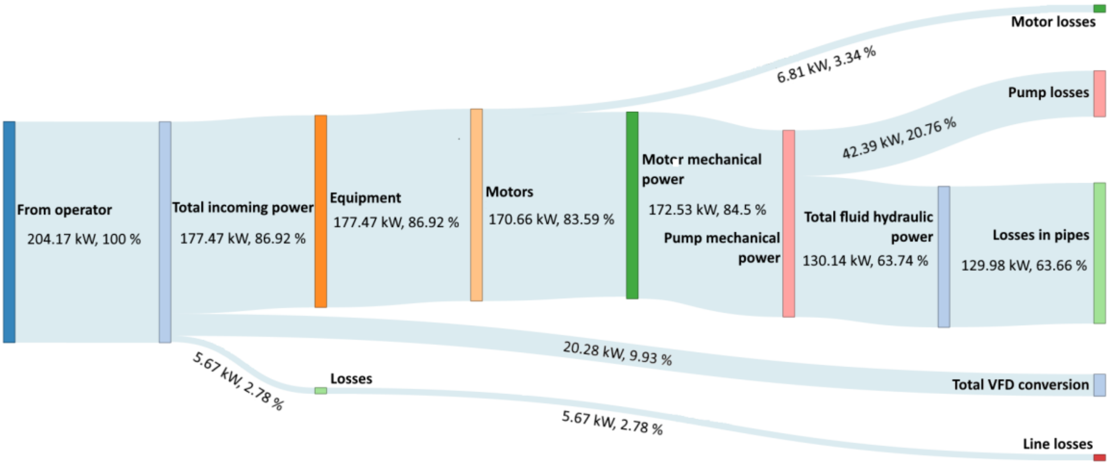

Figure 4. Condition BB Sankey diagram with a pipe system with a bigger diameter

TABLE 3. CONDITION BB PUMP EFFECTIVENESS

Title	Manufacturer	Model	η, %	η_{max}%	PR, %
Pump station I pumps	Grundfos	TP 150-660/4 A-F-A-BAQE - 98858121	77.06	81.4	94.6
Pump station II pumps	Grundfos	TP 100-1410/2 A3-F-O-DAQF - 99088540	74.87	77.5	96.6

The next step is to choose a combination of pumps to match the flow of case AA. It was determined that the most applicable pumps in pump station 1 are Grundfos TP 150-660/4 A-F-A-BAQE, in pump station 2 – Grundfos TP 100-800/2 A3-F-O-DAQF. With such pumps flow of water reached 490 m^3/h. This value is much closer to flow calculated in case AA.

The variation of pumps types allows to reach different work states. Even though controlling pumps with VFD changes the pumps characteristics, different models characteristics are changed differently.

VI. CASE CC

The goal of this case is to further analyze case AA by both lowering and raising the system reserved pressure by 5%. The overpressure creates and determines additional hydraulic losses. The goal of this case is to determine the effect of such changes..

To start with, the case of lowering the pressure by 5% will be analyzed (25% reserve pressure). The change is accomplished by configuring VFD output frequency to lower the RPM of electrical motors. With these conditions calculated flow is equal to 440 m^3/h. The Sankey diagram of this case is shown in Figure 5.

The next case is the opposite of the first one: the reserved pressure is raised by 5% (35% reserve pressure). This change is also applied to both pump stations. Calculated flow during with these conditions is 507 m^3/h. Sankey diagram of this case is shown Figure 6.

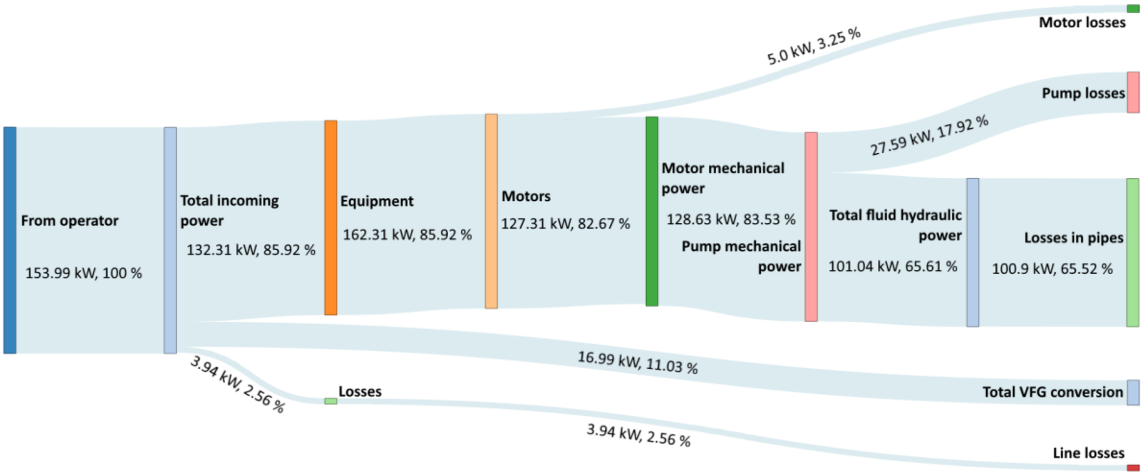

Figure 5. Case CC Sankey diagram with 5% lower reserved pressure

TABLE 4. CASE CC PUMP EFFECTIVENESS

Title	Manufacturer	Model	η, %	η_{max}, %	PR, %	RPM
Pump station I pumps	Grundfos	TP 150-660/4 A-F-A-BAQE - 98858121	81.32	81.4	99,9	1938
Pump station II pumps	Grundfos	TP 100-1410/2 A3-F-O-DAQF - 99088540	74.41	77.5	99,2	2028

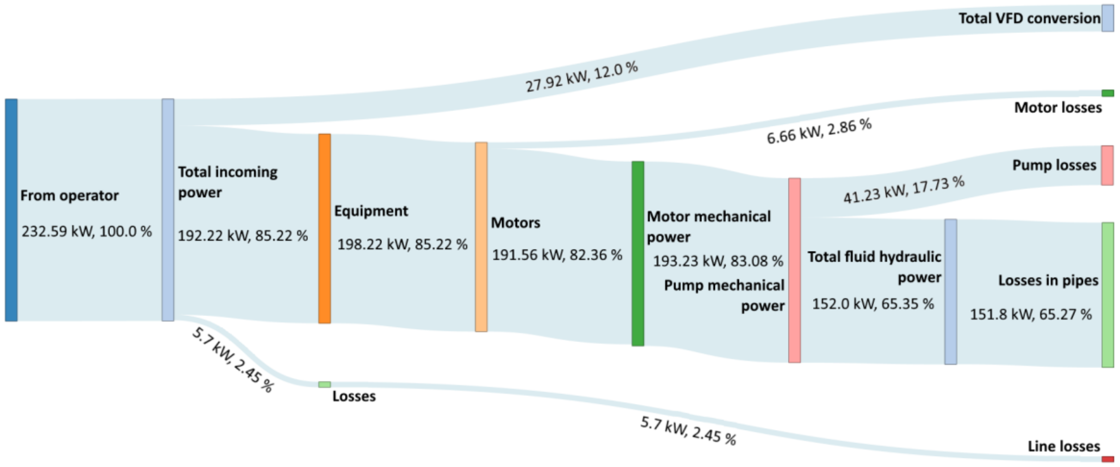

Figure 6. Case CC Sankey diagram with 5% raised reserved pressure

TABLE 5. CASE CC PUMP EFFECTIVENESS

Title	Manufacturer	Model	η, %	η_{max}, %	PR, %	RPM
Pump station I pumps	Grundfos	TP 150-660/4 A-F-A-BAQE - 98858121	81.32	81.4	99.9	2266
Pump station II pumps	Grundfos	TP 100-1410/2 A3-F-O-DAQF - 99088540	74.41	77.5	99.2	2296

CONCLUSIONS

To sum up the results of both cases Table 6 is created. The energy economy of both cases is estimated by firstly calculating the total energy consumed during the whole season. It was assumed, that the length of the heating season is 180 days and the price of energy is 0.08 EUR/kWh. Calculations indicates that overpressure causes additional hydraulic losses in the system, which then relate in increased consumed energy and costs.

The consumed energy changes with changing reserve pressure from 25% to 30% and from 30% to 35% are different. Hydraulic losses do not grow linearly depending on pressure changes. However, the 5% change of system pressure has an extensive influence upon the consumption of power from the electricity distributor. Between all overpressure intervals of the performed analysis the electrical power consumption fluctuates up to 38.55%.

TABLE 6. CASE CC OVERPRESSURE INFLUENCE UPON ENERGY CONSUMPTION PER SEASON

Reserve overpressure	Power from operator, kW	Electrical energy/season, kWh	Expenses/season, EUR	Difference from case AA, EUR	Difference from case AA price, %
25 %	153.99	665236.8	53218.944	17342.21	-24.58
30 % (AA case)	204.17	882014.4	70561.152	0.00	0.00
35 %	232.59	1004788.8	80383.104	-9821.95	13.92
Length of heating season: 180d					
Price for kWh: 0.08 EUR					

Having done case CC hydraulic flow analysis and given the data in Table 6 we can assume that the added overpressure lowers the energy effectiveness of the system. To lower the hydraulic losses as much as possible, the reserve pressure in the system must be minimized. However, it must be noted the reserved pressure is a necessity in every network since it is required to ensure stability in case of various equipment and system failures. To make system as economical as possible reserved overpressure must be designed carefully and should be minimalized while at the same time ensuring the stability of the network.

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