TALLINN UNIVERSITY OF TECHNOLOGY
SCHOOL OF ENGINEERING
Department of Energy Technology

THE PERFORMANCE EFFECT OF REPLACING AN OLD DISTRICT HEATING SUBSTATION

VANA KAUGKÜTTE SOOJUSSÕLME ASENDAMISE MÕJU PARAMEETRITELE

MASTER THESIS

Student: Dabrel Prits

Student code: 183024MASM

Supervisor: Eduard Latõšov, Associate Professor

Tallinn 2022

(*On the reverse side of the title page*)

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Energy Technology and Thermal Engineering

THESIS TASK

Student: Dabrel Prits, 183024MASM

Study programme: Energy Technology and Thermal Engineering (code and title)
main speciality:
Supervisor(s): Associate Professor and Programme Director, Eduard Latõšov
Consultants: …………………………………………………………….(name, position)
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Thesis topic:

The Performance Effect of Replacing an Old District Heating Substation (in English)
Vana kaugkütte soojussõlme asendamise mõju parameetritele (in Estonian)

Thesis main objectives:

1) Setting up a test site for 2-Stage heating substation testing to gather data
2) and verify calcium carbonate build-up in the domestic hot water heat exchanger.
3) Analysis of district heating substation gathered data and comparing it to the old heating substation in the test site to understand the parameter change from old to new.
4) Comparing the test site’s heating substation to other similar size sites.
5) Analysing a case where a large number of low performing heating substations in the Tallinn district heating network would be replaced by a new one with the test site’s new heating substation parameters with the main objective to understand the potential primary temperature difference increase.

Thesis tasks and time schedule:

No	Task description	Deadline
1.	Choosing the Thesis topic	Autumn 2020
2.	Set up a test site with a 2-Stage heating substation	31.12.2020
3.	Data gathered for analysis	31.01.2022
4.	Data converted to an analysable set	28.02.2022
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Supervisor: ……………………………………….. "......."....................201….a

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Consultant: ……………………..................... "......."....................201….a

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PREFACE

District heating companies have limited options when it comes to influencing customers' temperature performance to get the best dT out of their HSS. Every dT degree, every cubic of volume pumped unnecessarily, and every overconsumed MW in the district heating network have huge monetary implications for the DHC (district heating company) and indirectly to the consumer through price. Thus, it is paramount to use the technologies best applicable for the particular DHN (district heating network), be it then parallel design or 2-stage heating substation (2S-HSS) and/or HSS with peak shaving.

During the 90s, with the Word Bank money, thousands of heating substations were installed in Estonia to transfer from the Soviet era's direct connection to the indirect connection. Exact data does not exist, but hundreds of these were 2S-HSS. Nowadays only some 2S-HSS are in use in Tallinn, others are either changed or built to parallel HSS. It is believed by market participants that the main reason is the high calcium concentration in Tallinn's water that caused a build-up of lime-scale and with that leakage of heat exchangers.

To address this problem a heating substation test site was set up in a five-storey apartment building in Tallinn. The building was chosen due to it being from the end of Soviet time and thus giving a broad comparison base for similar size buildings with parallel design HSS. Moreover, a clear picture is given what is the parameter improvement of replacing an old HSS and what the effect would be if lower-performing HSS would be replaced on a larger scale.

Hereafter then is the objective to give measurement-based verification in what aspect is the 2-S HSS superior and what should be kept in mind when implementing this design.

Thanks to Utilitas Tallinn AS for providing the opportunity for the test site project and for the heat meter data to do the comparative analysis. Ouman Automation is also in high regard for providing the Ounet infrastructure for data collection. The study was conducted relying on a full year's (2021) consumption data.

The thesis addresses the research problems and at the same time acts as an easily understandable instruction on what a heating substation is, what are the main components and how it works.

Warm appreciation to A. Hlebnikov, V. Mašatin, and A. Šablinski for suggestions on how to approach the topic with being restricted to heat meter data and my supervisor E. Latõšov for providing prompt feedback.

Keywords: Low-temperature district heating, Heating substation parameters, 2-stage heating substation, Efficient heat media usage, Primary temperature difference, Fouling of heat exchangers, Master Thesis

List of abbreviations

1S-HEX	1-step heat exchanger
1S-HSS	1-stage heating substation, parallel design
2S-HEX	2-step heat exchanger
2S-HSS	2-stage heating substation
DH	District heating
DHC	District heating company
DHN	District heating network
DHW	Domestic hot water
DHW-HEX	Domestic hot water HEX
dT’	Temperature difference prim, i.e on the primary side T1 – T2
dT’’	Temperature difference sec, i.e on the secondary side T4 – T3
HEX	Heat exchanger, in this work’s context, is mostly used as a brazed plate heat exchanger, unless otherwise stated; manufacturers’ literature uses the term BHE, i.e brazed heat exchanger [1], but HEX is easier on the brain.
H-HEX	Heating heat exchanger
HSS	Heating substation
LMTD	Logarithmic mean temperature difference (see section 1)
T1	Inlet temperature hot side, primary side flow temperature to the HSS, i.e temp. from the DHN
T2	Outlet temperature hot side, primary side return temperature from the HSS, i.e temp. returning to the DHN
T3	Inlet temperature cold side, secondary side return temperature, i.e temp. entering the HSS from the customer’s system
T4	Outlet temperature hot side, secondary-side supply temperature, i.e temperature entering customer’s system

INTRODUCTION

As very well-formulated by Oevelen et al.: Network temperatures play a major role in the overall efficiency of district heating networks. Low network temperatures are desirable because they allow high heat production efficiency and low network heat losses. Furthermore, low network temperatures benefit the injection of low-temperature renewable and excess heat sources. At the same time, a high temperature difference between supply and return pipes is desired to limit the network flow rate. This reduces pumping power and increases the network capacity. Whereas the network supply temperature is governed by the heat supply, the network return temperature is determined by the connected customers [1].

Moreover, Averfalk H et al. bring out what a low-temperature DHN enables: to extract more geothermal and solar energy, use less electricity for heat pumps, recover more from flue gas condensation, generate more electricity in CHP, higher heat storage capacity, lower heat distribution losses [2].

Latõšov et al. showed there are technical possibilities to decrease the network temperature in Tallinn's DHN [3]. To keep the district heating temperatures low, the secondary side systems calculation parameters, primarily the supply temperature from HSS, should also be kept low. How lot it can be, must be balanced against cost and other considerations. For example, the Swedish building code stipulated back in 1982 that the maximum supply temperate should be 55 to 60 °C [4]. This has an effect on HEX dimensioning.

A heat exchanger is a heat transfer apparatus that usually involves two flowing fluids separated by a solid wall. Heat is first transferred from the heat-carrying (hot) media to the heat exchanger wall by convection, through the wall by conduction, and from the wall to heat-receiving media (cold) again by convection [5].

Ciegel suggested that NTU (number of heat transfer units) values higher than 3 cannot usually be economically justified [5]. Averfalk and Werner suggested that in a future district heating network, the temperature difference between the district heating and the consumer should be greatly lowered and that has to be reflected in the heat exchangers, with a logarithmic mean temperature difference reduction to around 5-10 °C and thermal length increase to 6-8 NTU [6]. These high levels of NTU would mean the primary and secondary temperatures are very close to each other, as can be the case in district cooling for example. This high NTU values are first difficult to achieve in practice, at least with plate heat exchangers, but more important the HEX would be highly over-dimensioned, i.e., HEX would require too much surface area to achieve it. That said, if existing DHNs desire lower temperatures in the future, the HEX of today need to be over-dimensioned and, i.e., with high NTU values.

In addition, Guelpa et al. emphasise the importance of mass flow in the system and the heat stored in the heating circuit and the substation [7]. New and well-functioning heating substations help to better predict the parameters in DHN and therefore better exploit the heat stored in the wider system. New heating substations also enable new control systems to be used, like demand-side management to shave peak demand.

Heating substations do not have a standard heat demand pattern, but the morning peaks are easily recognisable, especially with the night set-back function [8]. This can affect other parameters, e.g., temperature difference on the primary side.

Intuitively, the 2S-HSS design has better dT’ than 1S-HSS, as is graphically shown by Werner and Frederiksen [4]. The question then becomes how it translates to real life and how applicable are 2-stage heating substation for Tallinn DHN and what should be considered when using this type of HSS.

Last but not least, as Mašatin et al. concluded, the main obstacle for 4th generation DHN to be realised is the consumers [9]. Furthermore, Gadd et al. found that in Sweden, compared to current distribution temperature levels, the elimination of faults in the HSS would result in half the decreased temperature level necessary for future district heating systems. The main faults in HSS are unsuitable heat load patterns, low average annual temperature difference (dT') and poor HSS control [10]. Thus, solutions that support and enable consumers to have lower temperatures in order to achieve lower temperatures in the DHN have to be analysed and used. From the perspective of DHC, the obvious step is heating substations and their parameters.

The thesis topic is important in helping DHC realise the efficiency potential that replacing old HSS has, looking into the future with lower temperatures and analysing if 2-stage HSS could be used in Tallinn and if so, what should be kept in mind when implementing this design. This is the basis for lower network temperature, lower losses and more efficient use of heat media, driving Tallinn DHN and others toward 4th generation networks. Further, Volkova et al. showed that Tallinn DHN’s future improvements should be focused on reducing the supply and return temperature, implementing renewable energy in heat production and addressing pipe conditions [11]. Seems obvious, but the literature analyses improvement of HSS on different aspects, mostly the control systems, and demand-side management etc., literature does not talk a lot about changing an old HSS to a new one.

The main goal of the thesis is to address this gap by analysing what improvement a new HSS can bring. The subgoal on this basis is to take a wider view of changing old HSSs to new, using old HSSs in Tallinn’s DHN as an exemplary case and to analyse 2S-HSS usage possibilities and 2S-HEX fouling.

1 Base equations and research approach

The thesis is mostly based on heat meter collected data from 2021. Other sources of data are the test site's temperature measurement data and data from equipment and dimensioning datasheets. A quantitative research approach that is characteristic of engineering-economic research based on collected data and resulting analysis is used. The analysis is twofold: visual graph analysis, i.e., descriptive statistics, is used to determine patterns and improvements in parameters. Thermal equation-based calculations are used where possible and appropriate.

Heat transfer (or heat) is thermal energy in transition due to a spatial temperature difference [12]. Heat meter data consists of DH supply temperature (T1), DH return temperature (T2), and flow volume. Heat transfer rate or heat load is then calculated as follows [5]:

$$Q = c * m * (T_1 - T_2), \tag{1.1}$$

where $c - specific\ heat\ capacity, \frac{J}{kg*K}$

$m - volume\ (or\ mass) flow\ rate, \frac{kg}{s}$

$T1 - temperature\ of\ a\ higher\ temperature\ heat\ media, hot\ side$

$T2 - temperature\ of\ a\ lower\ temperature\ heat\ media, hot\ side$

$(T_1 - T_2) - heat\ media\ temperature\ difference, also\ \Delta T\ or\ dT$

Most referred heat media temperature difference in DHN is the primary side temperature difference, in this study marked dT'. The study used a weighted dT' for referring to temperature differences in DHN. If not stated otherwise, all dT' are weighted average in a given period. The weighted average for large datasets is usually calculated using the spreadsheet tool Excel. With boolean logic, the formula for weighted average would look like this:

$$\text{Weighted average (dT}') \text{ value } = \frac{\Sigma(f_n * f_m)}{\Sigma f_n}, \tag{1.2}$$

where $f_n - value\ with\ weight = volume, \frac{m^3}{\mathrm{h}}$

$f_m - value\ being\ weighted = dT', °C$

For HEX calculations the SWEP SSP8 freeware tool is used. As the HEX is an integral part of HSS, it is important to understand the dependences and the heat transfer process parameters that have the largest effect on HEX dimensioning. HEX is calculated according to requirements and input data. Two important values should be understood that give a sense of how difficult duty is from a thermodynamical perspective. These are LMTD and NTU [13].

LMTD or logarithmic mean temperature difference shows how large the mean temperature difference between heat-carrying and heat receiving media is. A smaller LMTD means a larger heat exchange area is required. LMTD is characteristic of input parameters and has one value per HEX. LMTD is calculated as [14]:

$$LMTD = \frac{\Delta T_1 - \Delta T_2}{\frac{\Delta T_1}{\Delta T_2}}, \tag{1.3}$$

Where $\Delta T_1 = T_1 - T_4$

$\Delta T_2 = T_2 - T_3$

$T_3 - temperature\ inlet\ for\ cold\ side$

$T_4 - \ temperature\ outlet\ for\ cold\ side$

The number of heat transfer units (NTU) shows how thermodynamically difficult an operational case for the HEX is [13]. NTU is also called theta-value or thermal length and is different for both sides of HEX. NTU is calculated as:

$$NTU = \frac{\Delta T}{LMTD}, \tag{1.4}$$

where $\Delta T - temperature\ difference\ on\ one\ side$

The required power for pumping is directly proportional to the flow volume pumped (kg/s) and pressure drop (Pa) in the network and inversely proportional to pump efficiency. Total pressure drop is the sum of pressure drop in the supply and return pipes and the minimum pressure difference in the most peripheral heating substation [4]. Furthermore, in the heating substation parameter improvement context, it is important to know that pressure drop is directly proportional to the square of volume flow rate (kg/s), thus the required DHN pumping power is directly proportional to the third power of volume flow rate [4].

2 A heating substation

2.1 What is it

According to Estonian Power and Heat Association, *a heating substation is an industrially produced assembly connected to the measuring unit, domestic hot water-, heating-, ventilation- and expansion equipment; a heating substation consists of heat exchangers, primary- and secondary side control equipment, pumps, measuring devices, valves and other necessary armature and piping. The heating substation is used for heat transfer from the heating network to the property's heating and hot water system and the temperature control according to the set requirements.* [15]

Frederiksen and Werner define the heating substation as a unit in which the type of energy is being distributed is transformed from a higher to a lower level, in terms of one or more characteristics of energy-related parameters, and in which the energy transfer can be interrupted in case of a disturbance or for repair. [4]

Combining the two definitions it can be said that: a heating substation is a heat transfer and control equipment assembly used for transforming energy from a higher level to a lower. The heating substation separates the district heating network from the building's systems, the main components used are heat exchangers, pumps, valves and control equipment, e.g., controller and actuators. Usually, the heating substation is located near a property's DHN inlet, thus mostly in the basement of a building. Heating substation components are durable, need little servicing and are mostly quiet.

Figure 2.1. A HSS with 11 sections [16]

2.2 Heating substation designs

Heating substations can have a direct or indirect connection. In direct connection, the primary side heat media flows directly through the building's heating system, without a separation from the DHN, and the primary side energy is directly transferred to the radiators. Indirect HSS, as the name suggests, is hydraulically separated from the heating system by a heat exchanger where the heat transfer to the secondary side heat media happens [17]. An indirect system has many advantages, e.g., physical separation from the secondary system and parameters, thus better control over the heat exchange and avoiding potentially costly accidents from secondary side system leakage. This thesis concentrates on indirect connection.

Heating substations come in different shapes and sizes, differ from country to country and even inside a country, and are always calculated according to the customer's needs, i.e., considering the primary and secondary side temperatures, heat load and allowed pressure drop. A main common distinction of HSS is the design used. It is clear from the first sentence that the pipe sizing and equipment vary greatly.

The main designs are 1-stage parallel (1S-HSS) and 2-stage heating substations (2S-HSS). There exist many other possible configurations, some examples are 1-stage series, either with radiator or DHW on top; and 3-stage designs where district heating media first heats the DHW, then the H-HEX and then the DHW-HEX pre-heating stage [4].

Parallel design means that both the T1 inlets and outlets to T2 of DHW and heating HEX are parallel. 2-stage design means that the H-HEX primary return T2 does not flow directly back to DHN, but instead flows through the DHW-HEX pre-heating stage, thus further using the primary energy potential and reducing the T2 [4]. Parallel design drawing can be found in sub-paragraph 2.3. below, the most common 2S-HSS design is depicted.

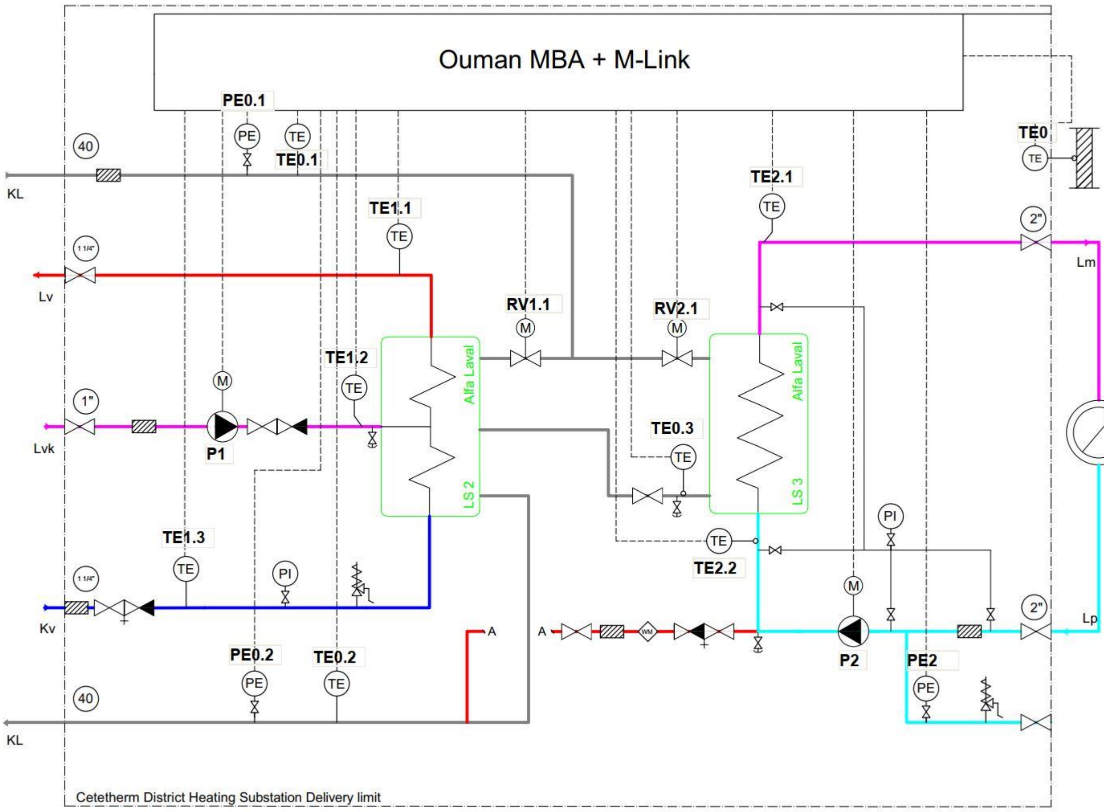


Figure 2.2. A typical 2-stage heating substation design [18]

As can be seen above, in the 2S-HSS design, the primary flow side is similar to 1S-HSS (see Figure 2.4), where both DHW-HEX and H-HEX get their heat straight from T1. The primary return side T2 is different. 2S-HSS use 2S-HEX with the pre-heating step. To better explain the flow inside a 2S-HEX and thus the working principle of 2S-HSS, Figure 2.3 shows a 2S-HEX and how heat media and DHW flow inside it.

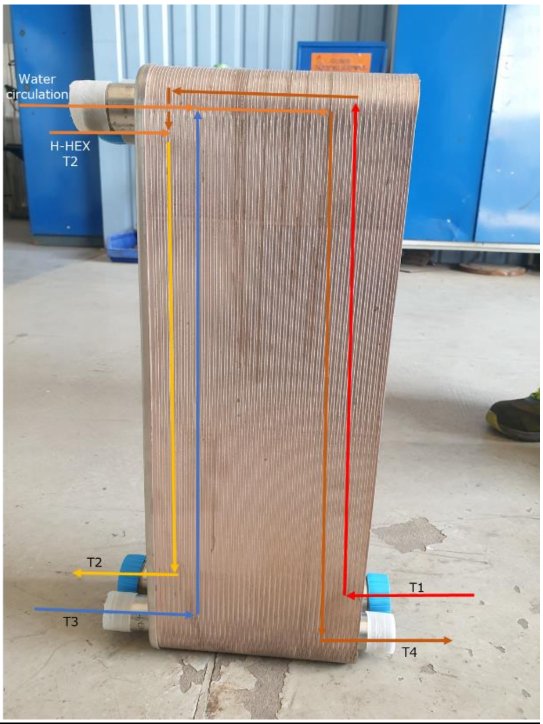


Figure 2.3. Flow principle of 2S-HEX

Table 2.1 describes the flow and how the flows mix in Figure 2.3 from the perspective connection.

Table 2.1. Flow principle of 2S-HSS from the perspective of connections

Connection	Description				Lenght travelled
T1	Enters the HEX from DHN	Heats the DHW to the required temperature	Is mixed with H-HEX T2 return and pre-heats cold water		Full HEX
T2	District heating media return to DHN				
T3	Enters HEX	Is pre-heated by the mix of H-HEX T2 return and cooled T1	DHW is mixed with DHW circulation	DHW temperature is raised to the required level by T1	Full HEX
T4	DHW flow to consumers				
H-HEX, T2	Enters the HEX from H-HEX T2 return	Is mixed with cooled T1	Pre-heats DHW before flowing back to T2 in DHN		Half a HEX
Water circulation	Enters the HEX from the building's DHW circulation return	Is mixed with pre-heated T3	DHW temperature is raised to the required level by T1	Exit from T4 to consumer	Half a HEX

2.3 Components of HSS

There are a variety of HSS designs from parallel to different 2-stage designs as discussed in the previous section. Designs differ from country to country and even between different DHNs in a country. In essence, there are hundreds, probably thousands of creative designs that a HSS can have if the designing engineer so wishes. To make it easier to comprehend what are the main parts of a HSS, Figure 2.4 together with Table 2.2 is used to describe the main components used in HSS. The following figure is based on the Estonian Heat and Power Association's [15] suggestion for HSSs used in the Estonian market. There is a debatably high number of components and some that may be unnecessary, but it gives a good basis for showing the main components and explaining their purpose.

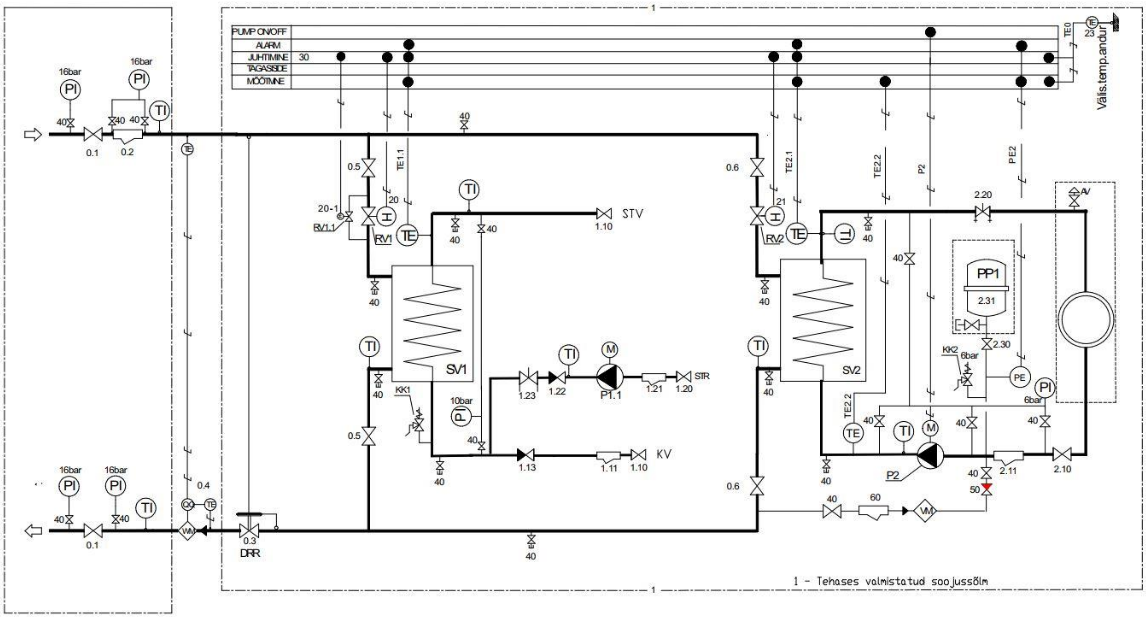


Figure 2.4. A typical Estonian parallel HSS design [16]

Comparing the 1S-HSS and 2S-HSS design drawings it is clear that the main difference is in the heating HEX primary return pipe. Designs are different, but the main components are the same thus this section about components is relevant for all HSS regardless of the design.

Table 2.2. Main components of HSS

Marking on figure Figure 2.4	Name	Purpose	Comments
0.1	Ball valve	Shuts off the flow of media from one part of the system to another	
0.2	Strainer	Keeps unwanted particles away from the delicate parts of the system	Used both on the primary and secondary side
0.3	Differential pressure regulator	Avoiding a HSS of having a too great of differential pressure	Too large differential pressure may hinder the functionality of primary regulating valves

RV1	Primary flow regulating valve	Controls the district heating media flow through a heat exchanger	Each section of a HSS has at least 1. Higher loads require 2 as depicted in the design
20	Motorised actuator	Controls the regulating valve to provide a set media temperature to the secondary side	
PI	Manometer	Measures system pressure	
TI	Thermometer	Measures media temperature	
TE	Temperature sensor	Digitally measures and transmits media temperature	Used both for control and informative measuring purposes
PE	Pressure sensor	Digitally measures and transmits media system pressure	
P1.1	Circulation pump	Provides consumers with the required flow of media	
Not explicitly shown in the design	Controller	Controls the regulating valve by sending signals to an actuator	The controller uses signals from temperature sensors to keep the media temperature at a given set-point or dependency graph
SV1	Heat exchanger	Transfer heat from one media to another	Usually, every section of a HSS is separated from the primary side by a HEX
PP1	Pressure vessel	Compensates thermal expansion of a closed system	
KK1	Over-pressure (safety) valve	Protects the system from exceeding the pressure limit	Safety valves are required to protect the equipment and piping connections
1.13	One-way valve	Restrict the flow of media to one direction	
2.20	Balancing valve	Enables to restrict the flow amount to given criteria	
WM	Flow meter	Measures how much primary heating media is used	
QQ	Heat meter	Calculates and transmits how much heat is used by using temperature primary sensor and flow data	DHC use it for measuring HSS parameters and for invoicing

2S-HSS has generally, depending on the HSS dimensioning methodology, more heat exchange area to accommodate the summer temperatures without the H-HEX pre-heating the cold water. With the same parameters, 60/25; 8/55 for DHW and 100/53;

50/70 for H-HEX, the SWEP SSP8 calculation program gives a 15% larger HEX surface area for the 2S-HSS.
A bit larger surface area cost can be oftentimes offset by the ease of construction for 2S-HSS. It is a more compact design, requiring less piping (or connections) and welding jobs to be performed. This in turn means, it is easier to produce standard parts into stock and the construction time of HSS is also smaller.

2.4 Control logic of HSS

HSS, like many other industrial application processes, is controlled by a PID controller. PID controller stands for a proportional-integral-derivative controller. Proportional gain is the difference between the real and desired value, with just proportional gain, a controller would never achieve the set-point value in a closed-loop system. Therefore, integral action makes it possible to achieve equality between the desired and real value, as a constant error produces an increasing controller output. Derivative action means the changes in desired value can be anticipated and appropriate actions taken before the actual change in value [19].
In essence, what a PID controller does, is it gets an input, in the case of HSS, from a temperature sensor, as can be seen in the Figure 2.3 Supply T, and then compares the actual temperature to the set-point or desired temperature and gives an output signal to a control element [20]. In the case of HSS, the output is given to the electric control valve, i.e., to regulating valve actuator. Nowadays, most used actuators are with 0-10 V input signals. Therefore, simply put, the PID controller gives the signal to an actuator to open. The closed control loop checks whether the desired temperature is reached. If the desired temperature is reached, the PID controller gives an actuator a signal to start closing. More accurately, the controller lowers the control signal and the actuator starts to close.

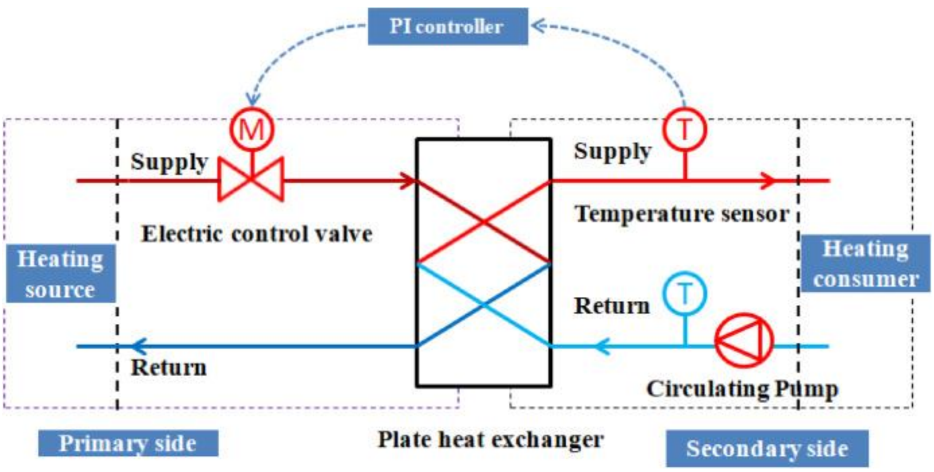


Figure 2.5 Control logic of a HSS [21]

DHW has a set-point that the controller tries to reach, usually 55 °C (a constant value). Heating and Ventilation systems use heating graphs that are dependent on outside temperature, i.e., when temperature decreases, the heating/ventilation supply temperature increases to compensate for the inside and outside temperature difference. Moreover, many HSS are not working in stable conditions resulting in flow and pressure oscillations due to nonlinearities of valve and plate heat exchanger sensor delay and improperly tuned controller [22].

2.5 Main reasons for malfunctioning HSS

High return temperatures and low dT' are unfavourable for DHN. Around 30% of malfunctions are due to secondary components, experienced by Swedish DHCs [4], and others by faults or malfunctions in the HSS. The most common faults and malfunctions identified in district heating installation of buildings are in brief [2] [4]:

- Malfunctions related to the secondary side of the heating installation, mostly poor balancing of space heating systems and shunts or bypasses
- Too high supply temperature set-point for both space heating and domestic hot water
- Oversized control valves and broken valves or actuators
- Broken controllers and misplaced temperature sensors
- Faults concerning HEX

Of the main faults and malfunction given above, these make up, in the order of mentioning in the list, 28 %, 35 %, 14 %, 12% and 8 % respectively. Others are 3 % [2] [4]. Different approaches to detecting malfunctions have been proposed in the literature, one important direction is to use machine learning [23]. It is clear from here why it is important for DHCs to work with customers in improving the HSS used and that installing a new HSS can alleviate all the problems but the secondary side.

2.6 T1 influence on HEX parameters

HEX calculations with different prim temperatures to exemplify how the main parameters like NTU and LMTD are affected moving toward 4 gen DHN. Calculations were done using SWEP SSP8 freeware HEX calculation software. Theoretical HEX calculation can be done to better understand the underlying relations in heat transfer, but heat meter data does not enable doing it in the real world. The following calculation is forward-looking, i.e., choosing what the future temperature should be, what is the appropriate HEX suitable for low temperatures and what the parameters are when we implement a HEX calculated to low parameters but use it with higher parameters.

Table 2.3 shows the main parameter changes when T1 is changed, and other values are kept the same. Load is taken 132 kW; HEX has 100 plates and 5,88 m^2 of heat exchange surface area. Base dimensioning sheet for T1 75 °C in Appendix nr 9 – Base dimensioning sheet of the HEX calculations.

Table 2.3. Heat exchanger parameter change with different T1

T1	**T3/T4**	**T2**	**Flow rate '/'', kg/s**	**NTU'/NTU''**	**LMTD**	**Re'/Re''**
100	50/70	50,1	0,63/1,58	9,55/3,83	5,22	602/1196
95	50/70	50,18	0,70/1,58	8,95/3,99	5,01	650/1196
90	50/70	50,33	0,79/1,58	8,27/4,17	4,8	710/1196
85	50/70	50,65	0,92/1,58	7,52/4,38	4,57	795/1196
80	50/70	51,33	1,1/1,58	6,68/4,66	4,29	924/1196
75	50/70	53,05	1,44/1,58	5,57/5,07	3,94	1179/1196

As can be seen from Table 2.3, the NTU values of 6-8, that are mentioned by Averfalk and Werner (see INTRODUCTION) as the benchmark for future, HEX can be achieved, but a lot larger HEX need to be installed than necessary today (see equations 1.1, 1.3 and 1.4). It is a decision that a DHC needs to make and a cost that a DH consumer needs to bear in order to be part of the greater energy mix of the future.

Over-dimensioning of the HEX would normally be unfavourable to flow characteristics, but by keeping the secondary side parameters constant, then the self-cleaning effect of a HEX does not suffer as the Reynolds number stays the same as it would be for higher T1 numbers. Of course, the Reynolds number would be higher if we take into consideration that when dimensioning for higher T1, the HEX would be smaller, but the Reynolds is the same for the HEX that we would be using for different T1 temperatures.

It is important to consider the primary side effect of 2x higher pressure drop when HEX surface area is kept constant, but T1 is reduced over the years.

To exemplify the LMTD relation to T1 and improve the visual understanding of the relation, when other temperatures are kept constant as above, see Figure 2.6.

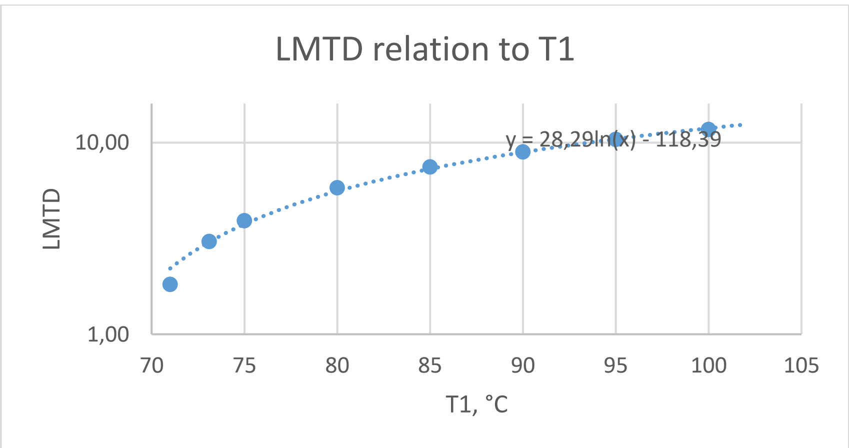


Figure 2.6. Logarithmic mean temperature relation to T1

2.7 2-step HEX implementation considerations:

Existing building envelope's internal systems (secondary system from the district heating perspective) need to be considered. Old radiators are dimensioned for high temperatures and thus do not have the heating surface necessary for lower temperatures. Cast iron also has a low heat conductivity, hence the heat transfer is inefficient and needs a larger conductivity surface area. Coupled with the knowledge that high-temperature graphs can induce lime-scale formation, not all secondary side systems are beneficial from the DHN perspective to be used with 2S-HSS.

2.7.1 Fouling of HEX

Fouling of HEX is an important topic for DHN. It has been shown that approximately 1,6 % primary energy savings can be achieved when proper measures are undertaken to keep the HEX clean [24]. It does not directly affect the price of a consumer whose HEX is dirty, i.e., consumer side heat losses thus consumer's invoice is not affected by inefficient heat transfer directly. The consumer is paying for the fouling indirectly through more primary energy used for heat production. Automatic fouling detection helps identify problematic HEX, but is not dealing with the underlying problem, effort is put into the research and development of such detection algorithms [24] [25]. Predictive maintenance is an important part of the future.

The build-up of lime-scale can happen when there is little to no domestic hot water consumption, e.g., at night-time when the return temperature T2 from the H-HEX is high enough to heat the DHW's pre-heating part that is not flowing. To avoid it, 2S-HEX should not be used in cases where there can be a combination of high T2 (>50 °C) and no post-cooling of T2 in the pre-heater part of the DHW 2S-HEX. Usually, these temperatures can be reached in old buildings with high heating temperature graph requirements, e.g., 60/85 °C and with very low outside temperatures. On the other hand, cooling down high heating graphs is a good opportunity to lower DHN T2. A couple of possible heating graphs are shown below.

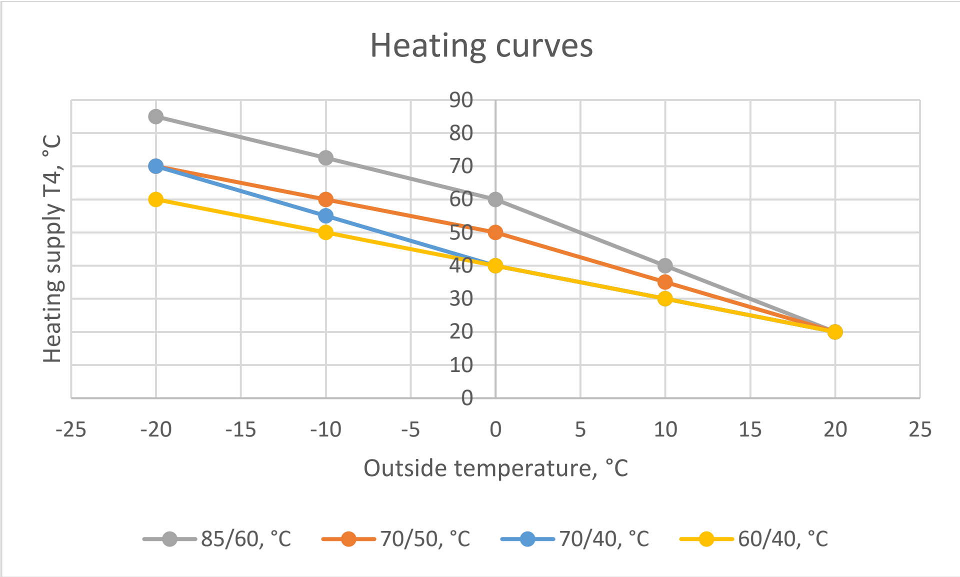


Figure 2.7. Supply temperatures of heating curves

In Figure 2.7 legend, for every graph line, the first value shows the heating supply temperature T4 and the second is the return from the heating system with an outside temperature of -20 °C, e.g., in the 85/60 graph, 85 °C would be the supply temperature and 60 °C would be the return to HSS. Lower temperature graphs like 70/50 °C and below should avoid the formation of lime-scale in the DHW 2S-HEX.

In the instances of high heating curves like 85/60 °C, a helping possibility might be to shut the circulation inlet blind and connect the circulation pipe to the cold water, as it is with the parallel design. With this connection style, the circulation water would be cooling the H-HEX T2 at all times and lime-scale formation could probably be avoided, depending on how low the outside temperature is and for how long it is cold outside, i.e., how high the T4 and thus T2 of H-HEX gets. This solution would also depend on the internal system of DHW, i.e., what the dT of DHW circulation is.

At the same time, this solution solves the problem for lower outside temperature and when the H-HEX T2 is higher than 50 °C, but when the outside temperature rises and the H-HEX T2 decreases, the circulation water would be heating the DHW-HEX return temperature T2 which is not favourable or acceptable from the perspective of DHN. Furthermore, DHW supply and thus circulation temperatures that affect the T2 can not be lowered either, as this is limited by the legionella growth concerns [26]

To get around these two problems, a bit more complex solution could be used. To use a 3-way valve before and between the DHW circulation and T3 of the DHW 2S-HEX, using H-HEX T2 as the input parameter. When the temperature of H-HEX T2 is higher than for example 50 °C, the DHW circulation is directed to enter the DHW-HEX from T3, but when the temperature is below the given criteria, circulation enters the DHW 2S-HEX from its regular inlet.

It is important to use an on-off type because the aim is to avoid lime-scale formation at higher H-HEX T2 temperatures and T2 increase at lower H-HEX T2 temperatures. The aim is not to mix the flows and the 0 – 10 V 3-way valve would make the system even more complex and vulnerable to incorrect parameter decisions and programming in the control system.

2.7.2 Water quality and dimensioning

2S-HSS are widely used in Finland, but according to the tests done for the Thesis, Tallinn's calcium concentration in mains water is 3 times higher than in Helsinki and the roughness of water in Tallinn is over 3 times higher (See Appendix 10 – Chemical content of mains water). Avoiding lime-scale formation is a part of the solution, the other part is the Ferrum particles found in the mains water due to old piping systems, as can be seen in 3.3. Thus, DHW-HEX needs to be cleaned at shorter intervals.

For lime-scale prevention, an option is to change the physical properties of water by using magnetic water treatment devices [27]. Many such devices already exist, at varying price levels. Knowledge development in the field is still in progress and a full understanding of how magnetic treatment affects water is yet to be developed [27]. When selecting such a device for wider-scale use or for a recommendation from DHC, it should be considered that with such devices, the strength of the magnetic field itself is important for the effect to occur, but much more essential is the magnetic field gradient [28]. Ferrum particles can be filtered out of the water, but with high concentrations, it is an added cost and hassle that apartment buildings are unlikely to undertake.

Besides the physical properties of water and its contents, an important aspect is the over-dimensioning of 2S-HEX and DHW-HEX in general, as these are calculated for summer, not winter temperatures. Due to over-dimensioning, the turbulent flow levels decrease if not go to the laminar flow, thus reducing or discarding the self-cleaning effect of HEX. Furthermore, laminar flow is associated with a thicker boundary layer and thus less efficient heat conduction and Reynolds number decrease means an increase in friction losses [29]. Of course, HEX designs that force turbulent flow, do exist [13], but natural self-cleaning is still important for keeping heat transfer surfaces clean as forced methods are associated with higher pressure losses. Turbulent flow can be forced by using, for example, chevron corrugation or treating HEX with nanofluids [30]

Stemming from over-dimensioned HEX, one consideration is to use smaller regulating valves to better control primary side temperature or if necessary parallel valves. It is especially apparent during the winter months when DHW regulating valve, which is dimensioned for summer temperatures, needs to perform well at its lower regulating level. Moreover, to accommodate other seasons besides summer, a HEX could be under-dimensioned to have a more accurate control and better self-cleaning properties.

3 OVERVIEW OF THE ANALYSIS

3.1 The set-up

3.1.1 On-site picture (others in the appendices), drawing and dimensioning sheet

The testing and comparison were done in Tallinn, in the district of Haabersti. Old HSS was installed in the year 1996, see Appendix 11 – Design of test site's old HSS, and no modifications were done to it. As it can be seen in the referred appendix, the HSS was designed to be a 2S-HSS, but in reality, it was a regular parallel design 1S-HSS. Haabersti was chosen as the comparison place because there were multiple buildings with the same design, thus giving a good comparison base as the buildings should have similar load characteristics for the HSS.

Figure 3.1. Picture of the new 2-stage heating substation at A36

Another reason for choosing this area was that the HSSs in the comparison buildings were from the same era and the parameters were not terrible, i.e., all comparison HSSs had a dT' > 30 °C. As this dT' is good in itself and gives a good base to broaden the comparison to other HSS that have dT' < 30 °C. Taking into comparison old HSS with higher dT', analysing their dT' improvement gives the analytical confidence that when

comparing HSS with lower dT’ we can be sure that the dT’ will be improved at least to the dT’ levels of the comparison sites used.
Particular HSS from that area was chosen as one of the less performing HSS concerning parameters. This gives a good idea of dT’ improvement and also the possibility to aggregate other HSS as one for comparison to eliminate parameter differences. The table below shows the primary side’s temperature differences before the test period, comparison for the winter months of January, February and December in 2019 is given. Winter months’ dT’ is relevant because most of the yearly consumption happens during these months and thus HSS have the largest technical and monetary impact on the DHN.

Table 3.1 dT' for comparison HSS before the test period. Weighted average dT' is given for January, February and December of 2019; dT’ is weighted with volume. Chosen test site is A36

Building	**dT' winter, °C**
A42	39,12
A38	35,55
A44	39,31
A34	39,83
A36	34,91
A26	32,73

All the above comparison sites had a HSS produced by CeteTherm in the second part of the 1990s. Some sites may have updated components, but the old HSS were the same. Chosen test site A36 had 1S-HSS with regulating valves produced by TA and HEX by CeteTherm. For heating Cetepac CP18 and for DHW Ceteplate CT110/23-1V were used. CeteTherm does not produce HEXs anymore, but these HEXs exist in the Alfa Laval nomenclature, respectively as, CB60 and M6 [31].
The new, installed heating substation is with a 2-stage set-up. For the design drawing, see Figure 2.2 and for technical data Appendix nr 8 – Dimensioning sheet of the new HSS for site A36.

3.1.2 Live chart with the HSS design

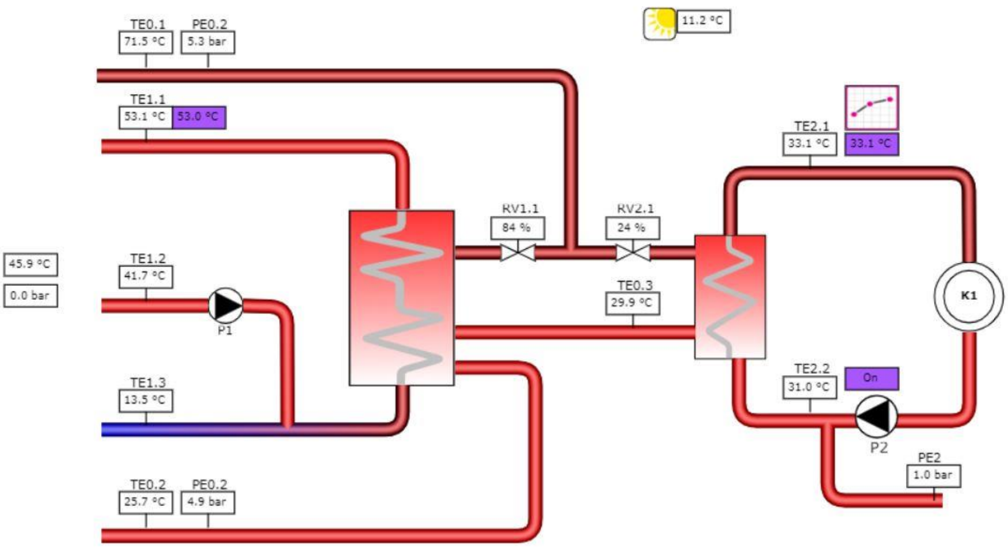


Figure 3.2. The live chart on the Ounet online platform

Ouman MBA controller together with their M-Link [32] Modbus TCP/IP [33] connection device was used for the HSS and sending the data online. Ouman's Ounet platform was used to monitor the HSS online and to collect data [34]. Nine Ouman (sensors: TMW, TMS, TMO, type NTC10 0 – 70 °C ± 0,2 °C [35], temperature sensors were used to collect data about the HSS, but this academic work is most of all concentrated on the dT' district heat meter data that was collected with Kamstrup Multical 66c [36] calibrated on 04.11.2019, using PT500 temperature sensors and DN20 Kamstrup Ulraflow 65S [37] ultrasonic flow sensor with a rated nominal flow of 3 m^3/h. Temperature sensor TE0.3 is of interest to understand what temperatures enter the DHW HEX from the heating HEX and what effect it has on the T2. Using heat meter data for analysis enables the comparison of many HSSs. All HSS have heat meters and these are calibrated at regular intervals, thus making sure the data is accurate for comparison. The controller wiring diagram as well as all HSS components can be found in the appendices, where the dimensioning sheet and specifications of the HSS are given, and some in the table below.

Table 3.2. Couple of main components for the new HSS. Dimensioning sheet can be found in the appendices

Product	Category	Purpose
Alfa Laval CB60-80L:2	HEX	Heat transfer to DHW
Alfa Laval CB60-50L 6C-HES	HEX	Heat transfer to the heating system
Grundfos Alpha 2 15-60	Pump	DHW circulation
Grundfos Magna 3 25-100	Pump	Heat circulation

3.2 Data and results

The data collection period was exactly 1 year, from 01.2021 to 12.2021. DHW supply temperature was modified by the customer on 21.02 from 55 to 53 degrees. The heating graph is set so that the supply temperature to the building, with -20 °C, is 63 °C, this is considered to be, from experience, the right graph from the Management of the Building's Association. As no tenant complaints during the test period were recorded, it can be considered the right heating graph.

The analysis is threefold: winter, summer and full-year are considered in different sub-sections. Aim to understand what the parameter changes were and if and to the extent the new HSS is superior. HSS parameters are dependent on secondary side systems, as discussed in 2.7.1. The main actions to lower secondary side temperatures, as shown in Low-Temperature District Heating Implementation Guidebook, are in the order from less expensive to most expensive: installation of thermostatic valves; hydronic balancing; supply temperature optimisation; replacing inefficient heat exchangers; replacing critical radiator; new replacing single-pipe heating systems with two-pipe systems; new low-temperature radiators; energy renovation [2].

3.2.1 Data preparation and integrity

PowerQuery data preparation tool was used to clean and uniform the data for analysis. To calculate and analyse data points, these need to match and be available for every minute. If data point where data was not collected due to no changes in the temperature, the upfill function was used to get the data for every minute.

Heat meter data preparation, negative temperature dT' values are considered 0 °C for graph building purposes, these values do not alter overall dT' values as these are weighted average values and during the hours when district heating was not provided (0 m^3/h flow through HSS), the resulting weighted dT' is also 0 °C.

The difference between heat meter primary temperatures and the test site's collected data is approx. 2 °C, heat meter temperatures are higher. The higher temperatures of heat meter data can be explained by the different types of temperature sensors used. The heat meter uses immersed temperature sensors on T1 and T2 lines that are inside the measured substance, but the sensors used for academic purposes were surface sensors. Temperature difference then comes from the pipe material "resisting" heat transfer from the DH water to the surface sensor and from the boundary layer that develops near the pipe surface [38]. All data is available in Appendix nr 2 – Pictures and data of the HSS.

Furthermore, outliers in the data are not searched for as these cannot be accurately detected in a heating substation [39] and heat meter data is rather accurate as it is the basis for invoicing and the heat meters are regularly calibrated.

3.2.2 Basis of the performance comparison

Network parameter performance coincides during comparison years as depicted in Figure 3.3. Thus, DHN functioned on similar parameters during the test years, i.e., the DHN weather dependant parameters were not lowered or raised and T1 corresponds to similar levels of load and dT' regardless of the year.

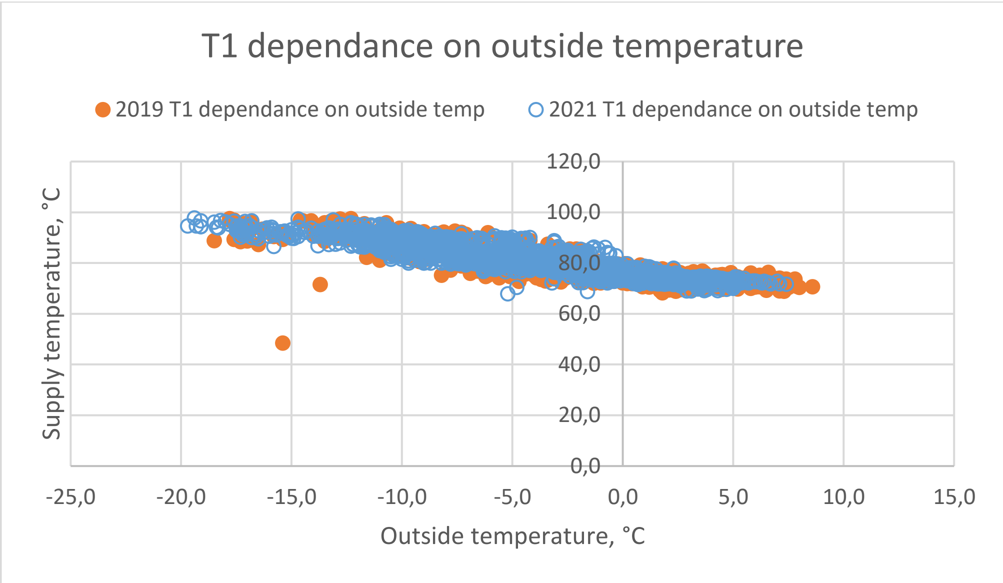


Figure 3.3 District heating primary supply temperature T1 dependence on the outside temperature during comparison years' winter months

2021 has a higher dT' level regardless of the T1 level. It can also be seen that during similar T1 levels, the new HSS performs better. From this can be concluded that T1 does not have a large effect on the dT performance and can thus be discarded in the dT comparison analysis, dT' is calculated as a weighted average value. In section 4, a similar HSS comparison analysis, it is seen that T1 affects dT', as is also clear from the heat transfer equation (equation 1.1). Moreover, in the context of old vs new HSS analysis, it can be discarded, especially as the relation is not linear, see Figure 2.6, and heat meter data is not enough to calculate these effects and concentrated on the parameter changes directly as this pronounced parameter changes would occur regardless of T1.

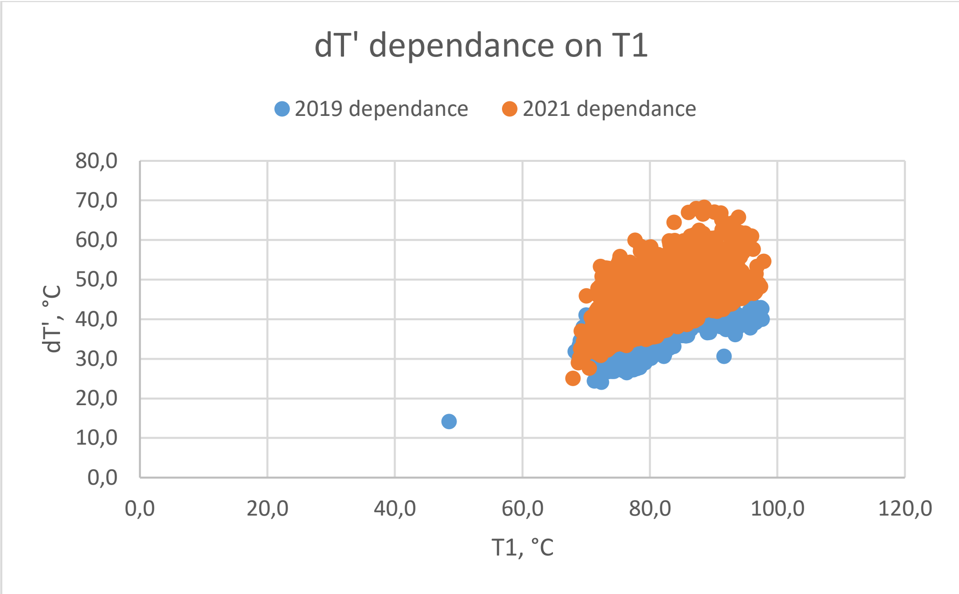


Figure 3.4. Test site's dT' dependence on T1 during winter months

Irrespective of the load level, the new HSS has a larger dT' during a similar load level comparison. This, and Figure 3.4. Test site's dT' dependence on T1 during winter months with Figure 3.3 District heating primary supply temperature T1 dependence on the outside temperature during comparison years' winter months prove that other factors do not have a major influence on the HSS and direct comparison of the new and old HSS is adequate. Figure 3.5 shows the performance of both, old and new, HSS during similar load levels.

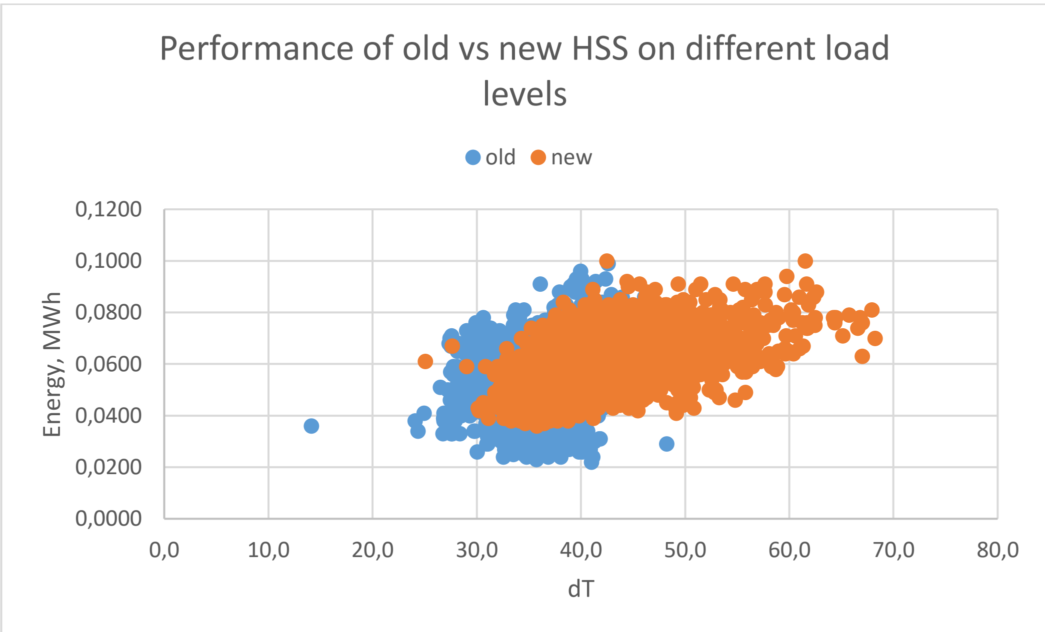


Figure 3.5 dT' performance of old vs new HSS during winter months showing better performance of new HSS dT' during the same load levels

Though, fouling of HEX surfaces and the heat transfer coefficient of old HEX can also play a role. We can ignore this as fouling is an integral part of a HEX being old and thermal resistance and heat transfer coefficient would be the same as both old and new HEX used stainless steel alloy for the heat transfer surfaces. Fouling is a natural part of an old HSS, irrespective of the HSS. As such, it is part of measured dT' and one of the potential parameter improvement reasons with a new HSS.

3.2.3 Winter Performance Improvement with the New HSS

As can be observed from Figure 3.6, the load levels are similar, but the characteristic parameters that determine the amount of heat exchange are very different. The current paragraph gives an understanding of what the main changes in parameters are when a new HSS is installed. The following figure depicts the "big picture" parameter change during the winter months.

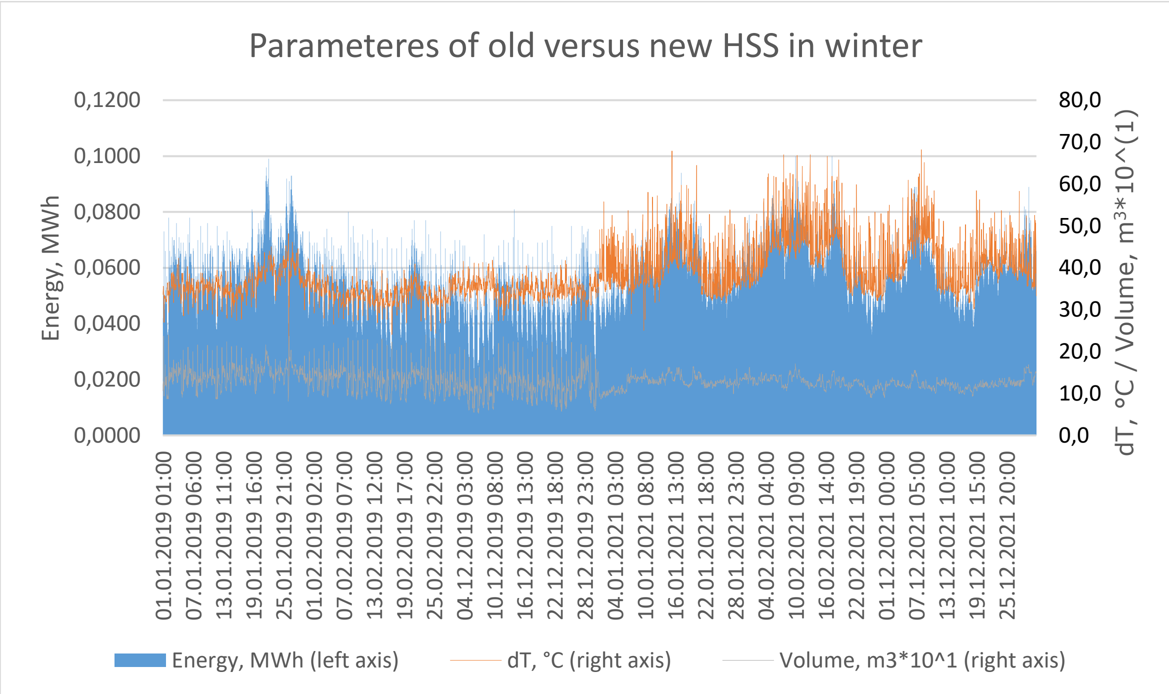


Figure 3.6. Depicts the parameter difference of the old and the new HSS during the winter months. New HSS was introduced in January 2021

From quantitative-qualitative with mostly quantitative control characteristics to qualitative control [40]. Though the control loop is still qualitative as the temperature is achieved through moving the regulating valve and thus controlling the flow, by looking at Figure 3.6 one could argue that the flow has become so smooth as if the control mechanism was qualitative. Stable and predictable flow is preferred from the DHN perspective.

Stable flow provides predicable pumping volumes and pressure drop over the HSS and thus means that flow characteristics and pressures in a given part of a DHN are more controlled. Less need for pressure stabilisation and fewer pressure fluctuations in DHN means a longer lifetime, fewer faults, and less downtime for more vulnerable parts, like connections, of DHN.

From that, it is also clear that a DHC can operate on lower pressure, if it is possible to separate areas with different pressure, in areas where there are few fluctuations in the flow. Pressure can be lowered because DHC needs not, just in case, to keep the pressure levels higher than necessary. Pressure can be lowered to accommodate the required, predictable flow volume. It is especially important in the context of lowering temperature levels in the DHN which naturally require more pumping power to deliver the same amount of heat (see Base equations and research approach). Stable and more predictable flow requirements can ease this pain point a bit for a DHC.

The heat transfer performance or effectiveness, heat media usage efficiency, has risen 16,9 % concerning heat transferred per volume and 12,9 % per temperature drop per T1, as shown in Table 3.3.

Table 3.3. Heat media usage efficiency changes in winter

	MWh/m3	**dT'/T1**
A36 old HSS	0,0402	0,4537
A36 new HSS	0,0484	0,5208
Performance change, %	16,9%	12,9%

3.2.4 Winter volume stability improvement

Wang et al. brought out that HSS operation instability mainly manifests as flow rate and pressure fluctuations, which have a negative effect on network hydraulic conditions, break the network thermal balance, reduce consumer comfort and increase the energy cost of the pumping system [41]. This very well underlines the importance of examining the HSSs' flow characteristics.

To get a better understanding of what the effect on volume has been, the box-and-whiskers plot is used in Figure 3.7. [42]. The box-and-whiskers plot is useful when visualising two similar datasets. This plot gives a concise visual of the outliers, extremes, median, average and in what range the flow is different % of the time. Especially important and useful as from Figure 3.6 it is clear that the flow volume for the new HSS became very smooth, but it does not give a concise, numerical, understanding of the changes.

Moreover, Figure 3.7 shows promising scaling down of the outliers and the extremes and holding a consistent flow band. From extremes, the lowest volume has raised from

0,53 m³/h in the old HSS to 0,92 m³/h on the new HSS. Rising a flow volume is not good in itself, but when considering the extremes, the high extreme of 2,08 m³/h in the old HSS and 1,59 m³/h in the new one, a 31 % decrease of high extremes and 43 % on outliers, the uniformity of flow volume is great, even the unexpectedly risen low extreme should suit the DHC as explained above. The volume range between extremes for the old HSS was 1,55 and 0,67 for the new HSS. The range between the extremes has decreased 2,31 times. Stable flow is a characteristic of 2S-HSS [4].

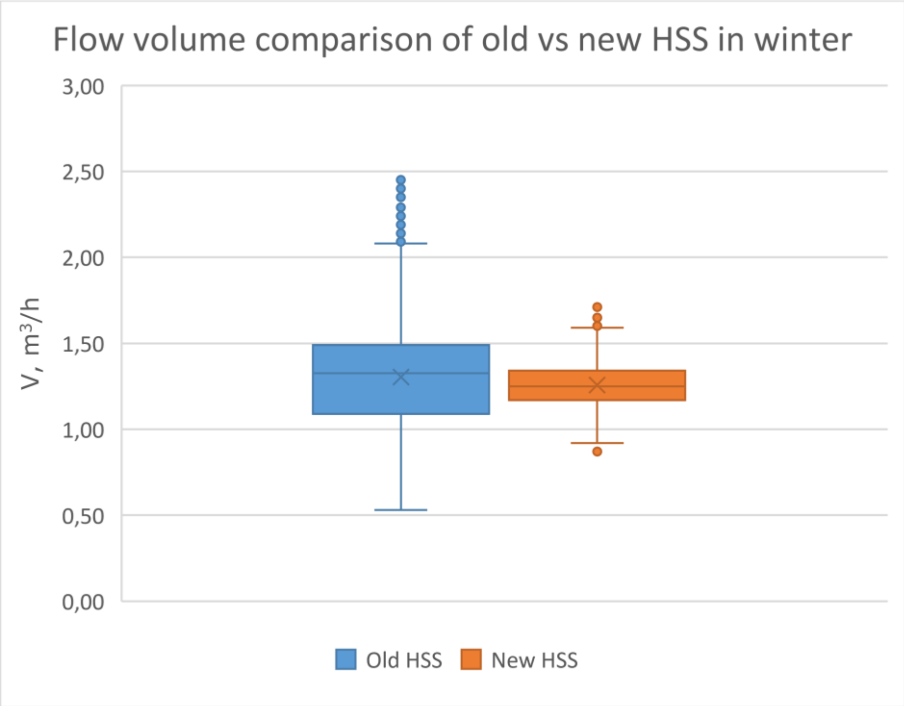


Figure 3.7. Flow volume comparison of the old vs new HSS during the winter months

Inter quartile range (IQR) of the old HSS is 0,4 and the IQR of the new is 0,17. IQR has reduced 2,35 times, new HSS has a volume 50% of the time between 1,17 and 1,34 which is a +- 7,7% deviation from the median as opposed to a deviation of +27% -37% in the old HSS. This stability has probably 2 main reasons: a more accurate actuator and controls system; and the fact that the new HSS is the 2-stage type where the return flow from the H-HEX enters the preheating of DHW-HEX and as part of the heat is transferred from the H-HEX return, less is needed from T1 and the flow volume is more stable, see the working principle of HSS in 2.1.

3.2.5 Winter dT’ improvement

New HSS shows much more dT’ correlation to demand, i.e., dT’ is lower when there is less consumption and higher when demand is higher. The New HSS median is almost as high as the higher extreme of old HSS, but the total heat surface area is only 5%

larger (for HEX parameter change reference, see Table 2.3) making the heat transfer more effective.

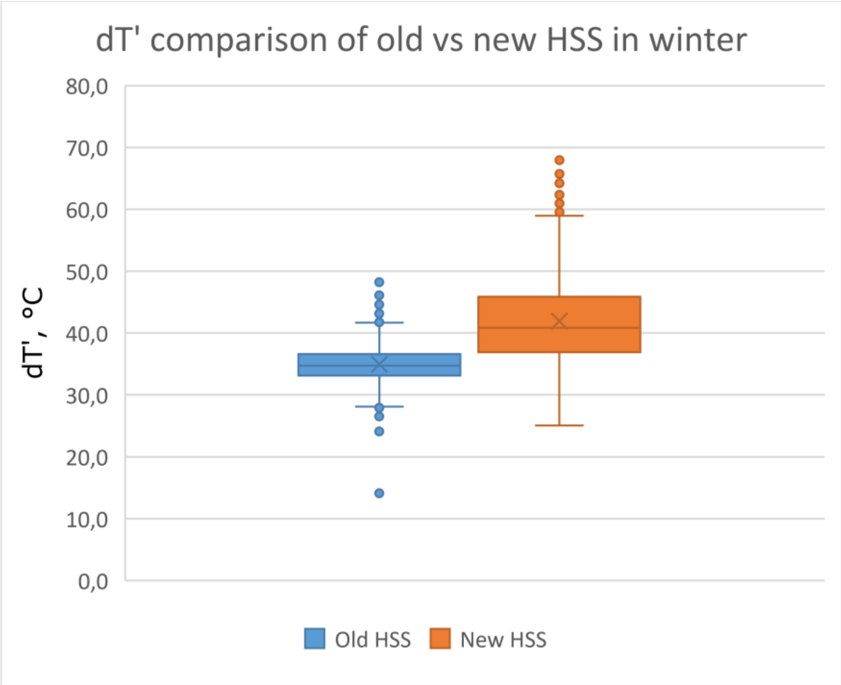


Figure 3.8. dT' comparison of the old vs new HSS during the winter months

Old HSS had a weighted average dT' of 34,91 °C, and new HSS has a dT' of 42,04 °C (see equation 1.2 above). Weighted average values are very similar to the average values, as can be seen in Figure 3.8, average values are 35 °C and 41,9 °C respectively. Old HSS had a small IQR of 3,4, referring to the HSS not responding well to the changes in demand. New HSS has an IQR of 8,9 and is on a higher level (the first quartile is higher than the third of old HSS).
25 % of lower dT' are between 25,1 °C and 36,9 °C owing to the fact that low demand means lower dT'. At the same time, it can be said that only 25% of new HSSs' dT' is lower than 36,9 °C, but 75% of old HSSs' dT' is below 36,6 °C. Higher 25% and 75% of values in the new HSS are above 45,8 °C and 36,9 °C respectively.

3.2.6 Full-year performance improvement

Parameter improvement is especially pronounced when looking at the full test period. Box-and-Whisker's plot is not very useful for a full year's data visualisation as the range becomes large, harder to comprehend and to draw a meaningful conclusion from. Thus, the full-year data is shown in Figure 3.9 as a combination of line and clustered column plots and summer parameters are given as Box-and-Whiskers plots. It can be seen that the building does not require heating for 5 months a year, from May to the end of September.

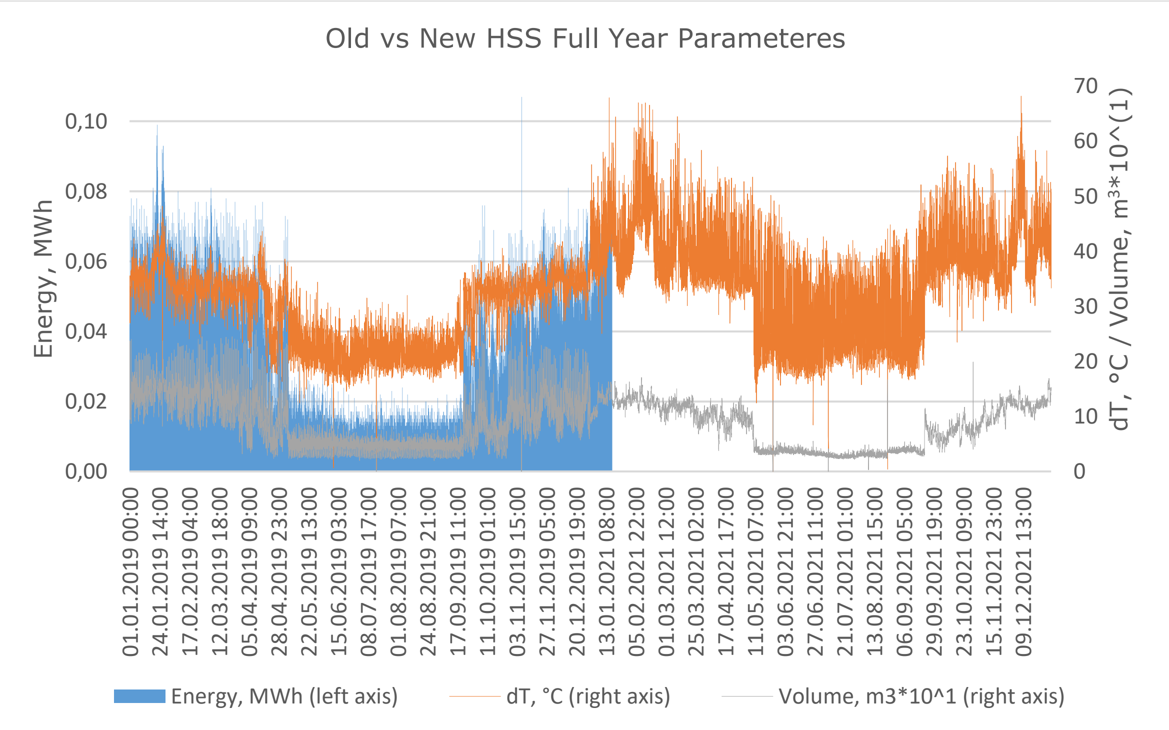


Figure 3.9. Old vs new HSS full-year parameters. New HSS data starts from 2021

New HSS delivers a weighted dT' improvement of 17,1 % over the year, from 31,28 °C in the old HSS to 37,71 °C in the new one. The average volume decrease is 8,8 %, from 0,867 m^3/h to 0,794 m^3/h. Table 3.4 shows the parameter improvement.

Table 3.4. dT' and V full-year parameters

	Old HSS	**New HSS**
Weighted dT', °C	31,28	37,71
Average V, m^3/h	0,867	0,794
m3/MWh	1,150	1,043
MWh/m3	0,042	0,046
dT'/T1	0,448	0,525

3.2.7 Summer performance improvement

As depicted in Figure 3.10, the lower level of dT' for the summer, i.e., June, July, and August, is 19-20 °C regardless of the age of HSS. This level in turn shows that the old HSS was functioning above average as many HSS in Tallinn's heating network perform below this level. Summer dT' is more dependent on T1 as the LMTD is much smaller than in the winter, average summer T1 was 64,5 °C for the old HSS and 63,8 °C for the new. Volume stability and temperature performance are clear indicators of the new HSS's performance superiority. As was seen in Figure 3.6 with winter performance, the new HSS temperature more accurately follows the demand of the building. Flow volume is stable compared to old HSS as was the case with winter parameters.

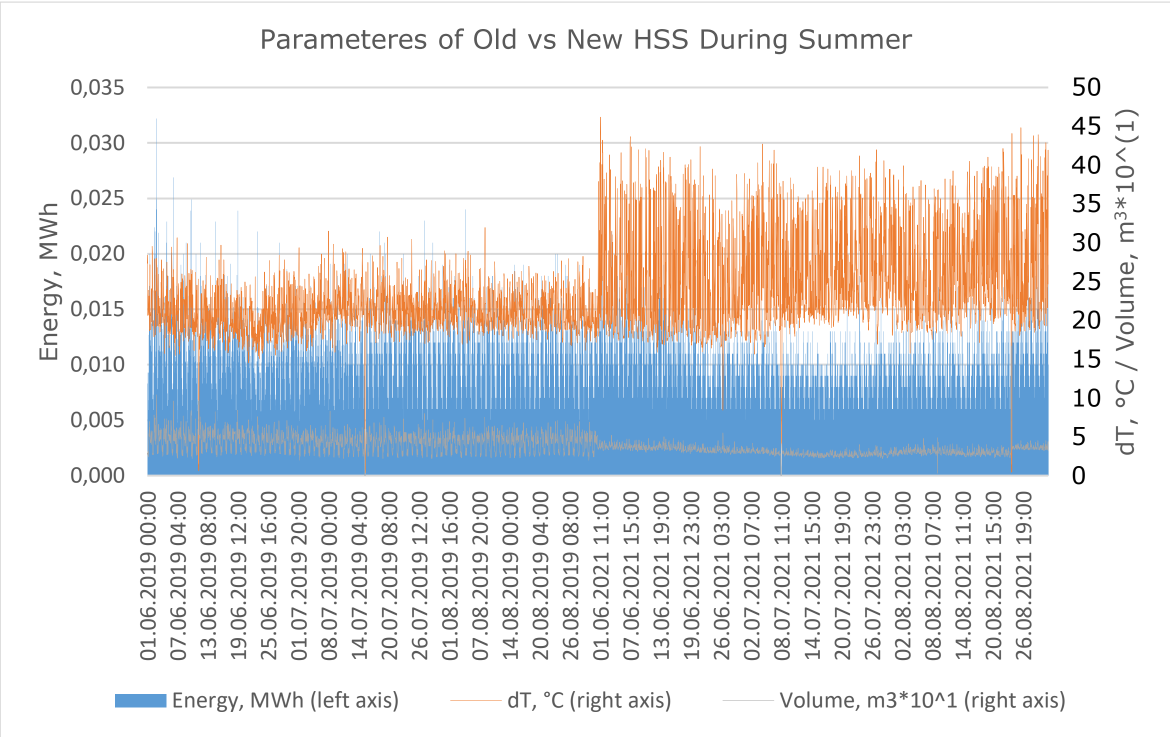


Figure 3.10 Parameters of the old vs new HSS during summer

Flow volume stability has increased even further compared to winter levels. It is self-explanatory as the winter demand change in the same three-month period is much greater than it is for the DHW demand. DHW demand can be considered constant throughout the year as the number of people consuming stays constant and the flow volume in the graph above reflects that well.

Figure 3.11 provides insight into the exact volume differences between the old and the new HSS. If the high extreme of the boxplot is considered to be the base flow that needs to be provided for the particular HSS at all times during summer, then we can conclude that the required base flow thought the HSS has decreased by 0,33 m^3/h, which a 73

% decrease. IQR decreased 2,6 times, from 0,18 m^3/h in the old to 0,07 m^3/h in the new. The difference between extremes decreased 2,5 times. Flow volume in the old HSS was 75% of the time under 0,52 m^3/h, whereas in the new HSS the number is 0,35 m^3/h.

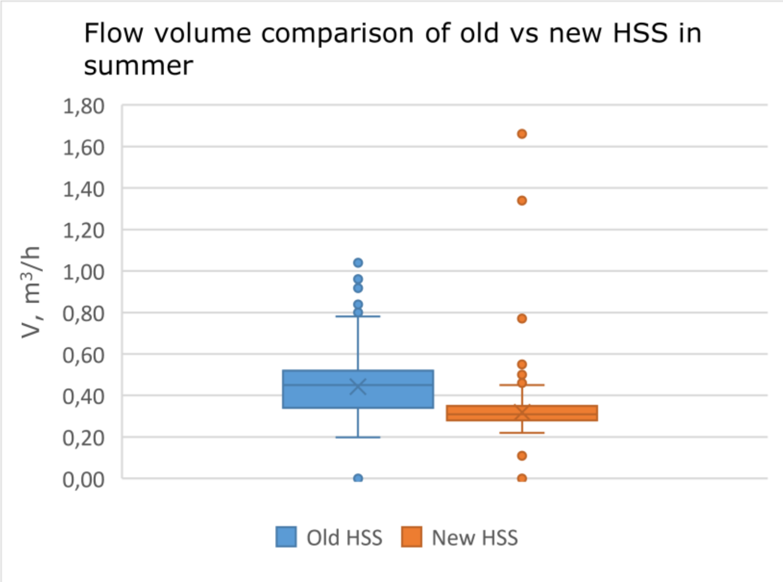


Figure 3.11 Flow volume comparison of the old vs new HSS during summer

Below, the dT' of summer is depicted. Like winter performance, the dT' has a considerable increase from a weighted average of 20,91 °C in the old HSS to 25,68 °C in the new. The analysis has shown the new 2S-HSS to be superior in parameters, but Figure 3.12 shows that the lower 25% of dT' values have a wider range than in the old HSS. This is probably due to the new HSS, temperature-wise, being more responsive to the demand. From that, expectedly the middle-temperature range or IQR is also much broader. At the same time, the top 25 % are higher than the highest values of the old HSS. For the DHC, higher values of dT' and predictability are preferred and, in the end, reflected in the price, which in turn are useful for the customer as well.

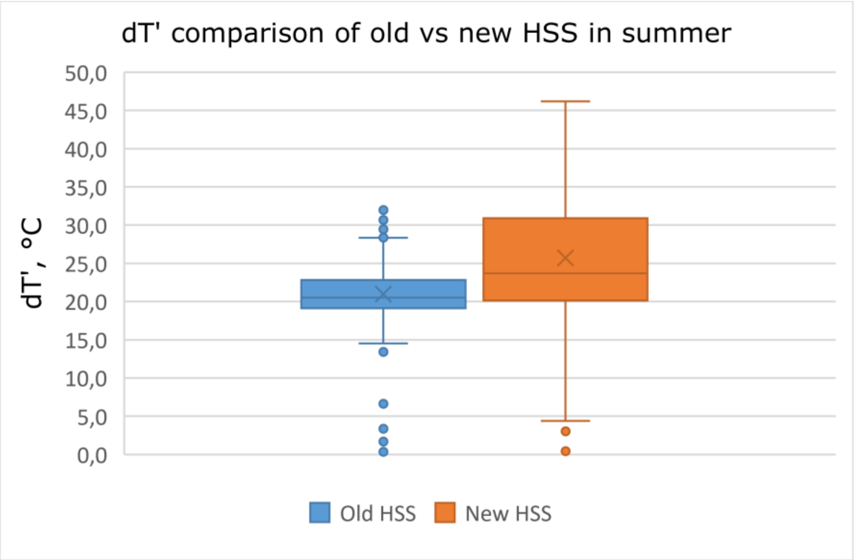


Figure 3.12 dT' comparison of the old vs new HSS during summer

3.2.8 Correlation of H-HEX T2 and DHN T2

The idea of a 2S-HSS is to further decrease the primary return temperature by using it for DHW pre-heating. This process is then dependent on the consumption of DHW. When there is consumption of DHW, then the difference between the T2 DHN and T2 H-HEX is positive, i.e., T2 DHN is lower than T2 of H-HEX. Moreover, to understand this dynamic, average values do not give much information and a shorter period needs to be looked at.

7 days from the 1-year test period was chosen. The period starts on Saturday the 16th of January 2021 and ends on the 23rd of January (see depiction in Figure 3.13). A higher and more stable DHW demand is beneficial for 2S-HSS. The test site's data shows that 2S-HSS is beneficial for further decreasing the temperature of primary return, compared to the temperature that would otherwise be returning from the H-HEX. Test data also confirms the importance of stable and/or higher DHW demand.

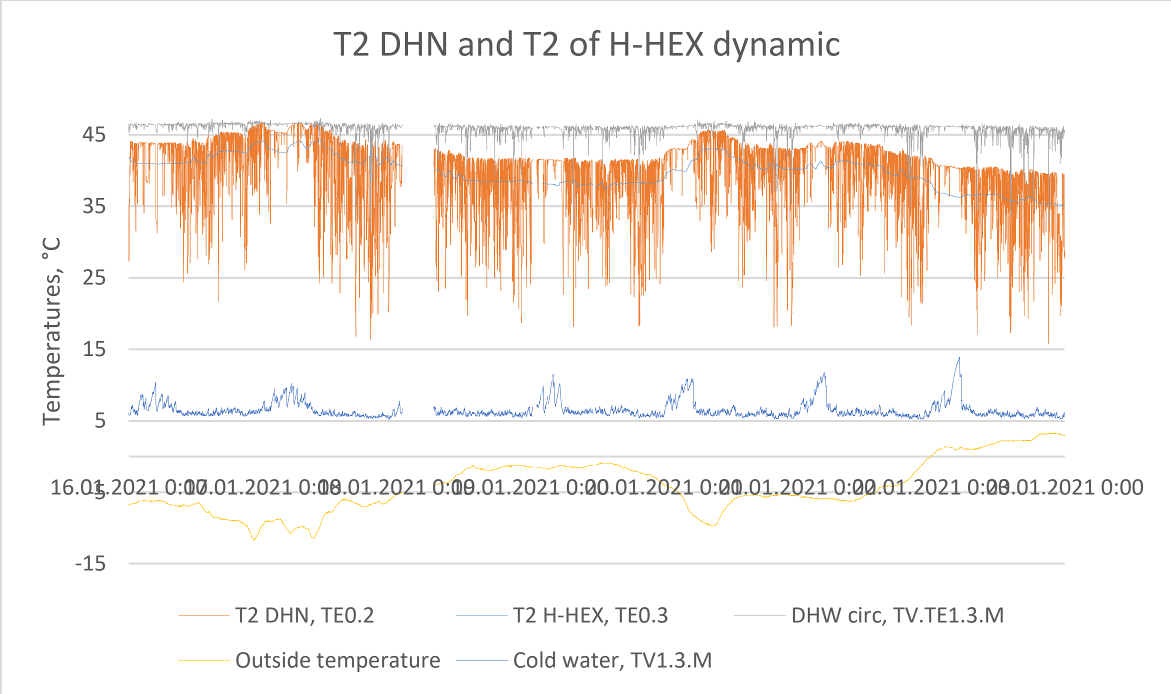


Figure 3.13. Test data dynamic of DHN T2 and H-HEX T2

Furthermore, during hours of no DHW demand, the T2 H-HEX can be lower than the resulting DHN return temperature T2. This is an unwanted consequence. Moreover, this is further underlined by the fact that H-HEX T2 is weather dependent, i.e., when outside temperature increases, the H-HEX T2 decreases and with that, the T2 DHN and T2 H-HEX dynamic works better when the H-HEX flow volume is smaller.

More to the point, low outside temperatures, depending on the contracted DHW demand, make it difficult to achieve a lower T2 DHN temperature than the H-HEX T2 at a given moment. It has to be mentioned that during non-consumption hours of DHW, the T2 DHN is only marginally higher than the T2 of H-HEX, but during DHW consumption, the T2 DHN is much lower.

Table 4.4 shows that on average 32% of the total heat is used for domestic hot water and the remaining 68% for heating. From that, it can be concluded that H-HEX has a 68% effect on the total T2. This, together with the test data, suggest the most suitable heating graph for a 2S-HSS is 40/60, as most of the winter is below -10 °C, and the 50/70 and 40/70 graphs are suitable as well.

As mentioned in subparagraph 2.7, the H-HEX T2 temperature (TE0.3) is limited by the return temperature of the building H-HEX T3 (TE2.2). Lower temperature graphs on the building side support the efforts of lower temperatures in DHN and a more efficient DHN. It is an important cooperation point and possibility between Heat and Power and Building Associations to work on building side normative stipulating lover temperature heating systems in the existing building stock.

3.3 Opening the DHW-HEX

HEX fouling is an important topic for the DHN as emphasised at the beginning of sub-paragraph 2.7.1. Consumers are indirectly paying for the fouling of their HEX. As a starting point for this thesis, the calcium concentration in the 2S-HEX pre-heating part was the biggest concern. These problems can be avoided with the right technical requirements from the DHC on how and in what buildings and with what temperature graphs these can be used.

DHW-HEX was cut into 3 pieces, see Figure 3.14, to see if and to what extent HEX is affected by fouling, either by lime-scale formation or by the consolidation of loose Ferrum particles from pipe corrosion (Ferrum oxide deposits on the heating surfaces), see Figure 3.15. DHW-HEX was cut using a metal cutting machine Luna MBH – 225. Cutting saw debris was removed by carefully blowing compressed air over the HEX with a compressor’s nozzle.

Figure 3.14. DHW-HEX in three pieces (left) and contents (right)

Tallinn’s water has 3 times the calcium concentration compared to Helsinki’s water, where 2S-HSS are regularly used (see Appendix 10 – Chemical content of mains water). Visual inspection did not reveal the build-up of lime-scale in the HEX channels; thus calcium concentration is not the primary concern. The primary concern seems to be fouling due to Ferrum particles (Ferrum oxide) in the water. Fe content in the mains water is not very high. From that, we can conclude that the issue is the old piping system, which is rusting, and the mains water is carrying floating debris with it. This can be both, the building’s piping itself and the mains piping system.

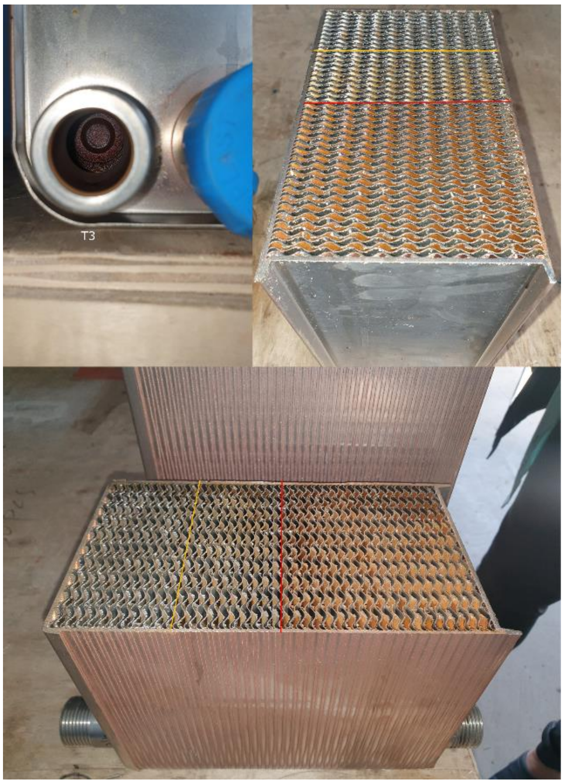


Figure 3.15. Contamination of 2S-HEX by DHW in Tallinn after operating for 1 year and 4 months

From Figure 3.15 it can be that the DHW 2S-HEX fouling is in 3 visually separable parts. Most intensive fouling has occurred in the pre-heating part of the HEX. The right side of the picture is the inlet of cold water (from the right side up to the red line), i.e., T3 of DHW-HEX. Supposedly this part of HEX is working as a strainer for the cold water. It is clear from the visual inspection that it is mostly Ferrum oxide particles attached to the heating surfaces.

Less fouling can be seen in the second step of the HEX, between the red and the orange lines. This is likely caused by some amount of Ferrum oxide particles making their way to the second stage as well due to not all of it being strained into the first stage. To the left of the orange line, it is almost clean. The reason for this difference is a mix of gravitational forces and pressure drop in the second stage which pulls the particles more into the first channels of the second stage. The reasons for a cleaner second stage are twofold: first, as mentioned, most particles are strained into the first stage; second, the second stage has more constant flow through as the DHW circulation flows through it, constantly cleaning the second stage.

The main understanding from cutting the 2S-HEX is that when these were to be used in Tallinn’s (or in Estonia) DHN on a larger scale, the suggestion is to make DHW-HEX cleaning a mandatory part of customer servicing of HSS. DHW 2S-HEX should be cleaned once a year to ensure the long lifetime of the HEX and good thermal parameters for the DHN.

Another suggestion is to make sure technical requirements stipulate exactly at what kind of buildings and with what kind of heating system temperature graphs this 2S-HEX can be used. When these two measures are undertaken, a 2S-HEX in the 2S-HSS is a high value-adding product for DHN and thus for the DHC. Furthermore, HEX dimensioning sheets need to be checked to make sure, if possible, that HEX turbulent flow characteristics, i.e., Reynolds number greater than 2000. Pictures and videos can be found in the appendix below.

4 Comparison of 2S and 1S consumption data

As can be seen in Figure 2.6, there is not a linear relationship between higher T1 and dT' and heat meters do not give enough input data, hence this could not be considered in the old vs new HSS analysis, but is more reliant on the volume stability and higher dT' levels.

In this section 2021 data is compared on an individual HSS basis which comprises 7 similar buildings and HSS and as if others on the same feed pipe with the 2S-HSS were one HSS. To average out the temperature difference, other comparison sites are taken as one 1S-HSS and then compared to the test site's 2S-HSS. The idea of this approach is to average the other HSS, these will become extra comparisons, besides the actual old HSS, based as if these were the old HSS.

When comparing the average dT' of individual HSS, the dT' 2019 vs 2021 is not much improved from higher T1, <3 degrees. It should also be kept in mind that with other HSS the volume has also risen regardless of the higher T1. Thus, the dT' improvement is from T1, but not the overall parameter improvement. In the test site, the parameter improvement is mostly from the new equipment.

4.1 Comparison sites/HSS

The basis of choosing the test site was addressed in section 3.1, here the characteristic of comparison sites are presented. The overall goal was to find similar buildings with similar demand and HSS, thus making the HSS parameters comparable. The building type and size were another consideration so that the results could be used to make a conclusion for a wider selection of buildings. Buildings with five storeys and with 2 entrances are perfect for that since Estonia and Tallinn have many buildings with similar proportions. The main attributes and how the DHN piping is located are presented in this sub-section. Building data is taken from Estonia's Building Registry.

Figure 4.1. Picture of A36 from 2019, how the test buildings look like [43]

All comparison sites have done outside renovation to some extent and sites A36 – A44 look the same from the outside and have the same size footprint. Comparison site A32is also the same size building. Main buildings' characteristics are shown in Table 4.1 and contracted load values in Table 4.2.

Table 4.1. Comparison buildings' attributes [44]

Site	Construc-tion year	Area under building, m2	Floor area, m2	Common area, m2	Building volume, m3	Floors	Apart-ments
A26	1994	627	3702,7	1375,3	11523	5	38
A32	1987	479	2766	1090,2	8792	5	28
A34	1988	626	3716,7	1349,8	11499	5	38
A36	1988	477	2758,6	1094,3	8754	5	37
A38	1988	473	2760,9	1097,3	8682	5	38
A42	1987	471	2704,2	1046,8	8615	5	38
A44	1987	471	2708,4	1047,2	8622	5	38

Table 4.2 Comparison buildings' contracted loads

Site	Total contracted load, MW	Contracted heating load, MW	Contracted DHW load, MW
A26	0,358	0,172	0,186
A32	0,283	0,132	0,151
A34	0,357	0,171	0,186
A36	0,283	0,132	0,151
A38	0,283	0,132	0,151
A42	0,283	0,132	0,151
A44	0,283	0,132	0,151

HSS location in the network determines the primary flow parameters of the HSS, i.e., temperature and pressure differences. Lower parameters mean a HSS needs to perform better to provide good heat media usage parameters. Figure 4.2 shows where comparison buildings are located in the network. All buildings have long distribution pipes connected to them, with some parts of primary piping inside the buildings.

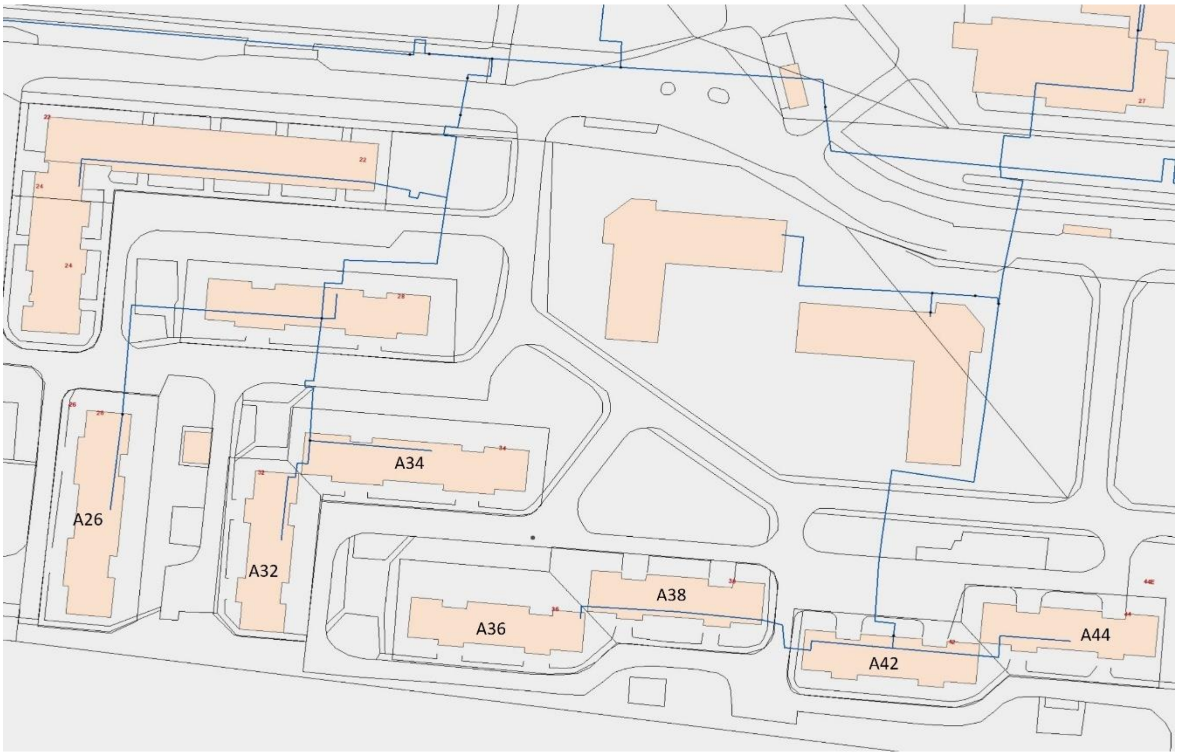


Figure 4.2. District heating piping in the comparison buildings' area [45]

Looking at the visual above it can be seen that the longest distribution piping is to sites A26 and A36. Table 4.3 confirms the length of piping affects the primary parameters in the HSS. Consumption data from 2021 shows the lowest T1 are in A26 and A36. Nevertheless, test site A36 with the new 2S-HSS shows high performance parameters.

Table 4.3. Comparison buildings' difference in yearly demand and primary parameters

Year	**Site**	**Demand, MWh/y**	**Flow volume, m^3/y**	**dT', °C**	**Peak demand, MWh**	**T1, °C**	**T2, °C**
2021	A26	306	8477	31,0	0,1	73,4	42,4
	A32	263	7683	29,5	0,094	75,7	46,2
	A34	363	8600	36,5	0,13	76,3	39,9
	A36	305	6956	37,7	0,1	75,1	37,4
	A38	299	8125	31,9	0,09	76,5	44,6
	A42	292	7036	36,0	0,1	79,1	43,1
	A44	265	5852	39,2	0,101	77,2	38,0

T1 in the sites varies between 73,4 °C and 79,2 °C, but the overall demand is very similar. Contracted loads of the comparison sites are considerably higher than peak demand values in Table 4.3, e.g., A36's contracted total load is 0,283 MW, but the peak load of the highest consumption hour is 0,1 MW. The peak value is of course average of an hour and values within the hour can be greater, but the peak value shows, as is expected, that the HSSa are over-dimensioned from the Soviet era. This is a common occurrence in Tallinn DHN it has been the enabler of T1 decrease in the wider DHN. If need be, there is still a little room for a T1 decrease in DHN, especially when old HSS are substituted with new well-performing ones.

In the comparison site appendix, it can be seen that the DHW hourly peaks, taken from the summer months consumption data, are not very high either. DHW peaks are approximately 0,03 MW for the HSS, and the contracted DHW loads at the same time are 0,15 MW, a difference of five times With DHW it is clear that peak demands within an hour vary greatly and are much higher than the heat meter measured hourly average. Though the peak demand in the comparison sites is similar, the specific heat demand is different.

DHW demand is calculated by taking an average of summarised demand for the summer months in 2019 and 2021. The average sum of the summer months is then multiplied by 4 to get the yearly DHW consumption. Ideally, a higher DHW load due to the lower temperature of cold water during colder months would be considered, but heat meters do not collect such data. For the purpose of this thesis, which is not to analyse different parts of demand, in particular, it is not that relevant. From the calculated DHW demand data it can be seen that demand, both heat and DHW, differs in the building on a considerable scale.

Table 4.4. Specific heat demand of comparison buildings

Site	**Specific thermal demand 2021, kWh/m²**	**Specific heat demand 2021, kWh/m²**	**Specific DHW demand 2021, kWh/m²**	**DHW of total demand, %**
A26	131,62	86,95	44,68	33,9%
A32	156,71	112,54	44,17	28,2%
A34	153,43	109,38	44,05	28,7%
A36	183,27	128,46	54,80	29,9%
A38	179,68	117,09	62,59	34,8%
A42	176,42	111,84	64,58	36,6%
A44	159,72	107,91	51,82	32,4%

Specific heat parameters show the test site A36 to have low efficiency as a building with a specific heat demand of 128,5 kWh/m^2. This indicates there might be more room for dT' improvement when the internal heating system is renovated and balanced. Approximately 32% of total heat demand is by domestic hot water heating.

4.2 Comparison of performance

Heat transfer is most effective when the least amount of heat transfer media is used to transfer heat, from heat transfer media to heat exchange surface, with the largest temperature drop possible. Since heat transfer is temperature difference driven and dependant on the highest temperature T1, then a good measure for performance is how much temperature drop occurred, in the transfer, per unit of higher temperature T1 driving the process. Comparison of performance analyses different HSS parameters and calculated values to determine which HSS perform better and if 2S-HSS performs better or worse in comparison to its parallel design peers.

Table 4.5 the main parameters regarding the performance of comparison sites in 2021. The highest amount of energy per volume is transferred by sites A44 and test site A36, 0,0485 MWh/m^3 and 0,0484 MWh/m^3 accordingly. The T1 temperature difference between these two sites is marginal 0,8 °C, to the benefit of site A44. The aforementioned temperature drop dT' per one degree of heat transfer media shows that A36 has the highest dT' per T1 of 0,5208. The second best dT' to T1 ratio is A44 with 0,5163. The least performing by heat transfer efficiency values is site A32 with 0,0391 MWh/m3 delivered and dT' per T1 of 0,4182, it also has the lowest weighted average delta dT' of 33,94 °C. Therefore dT' reflects the heat transfer media usage rather well.

Table 4.5. Winter 2021 heat media usage efficiency in comparison buildings, MWh/m^3

Site	T1, °C	dT', °C	MWh/m^3	dT'/T1	IQR dT', °C	IQR V, m^3/h
A36	80,71	42,04	0,0484	0,5208	9,0	0,17
A26	79,88	36,08	0,0417	0,4516	6,6	0,22
A32	81,17	33,94	0,0391	0,4182	4,7	0,38
A34	81,99	41,65	0,0481	0,5079	7,8	0,30
A38	82,24	37,02	0,0427	0,4501	7,6	0,20
A42	84,09	39,84	0,0460	0,4737	6,7	0,30
A44	81,51	42,09	0,0485	0,5163	5,5	0,33

The top 25 % of A36 dT' is above 45,8 °C, which is the highest of the comparison sites. The highest 50% dT' level is site A44 with 41,6 °C, followed by A36 with 40,9 °C. The highest 75% of values are also performed by A44 with 75% of dT' over 39,2 °C, corresponding value for A34 is 37,6 °C and 36,9 °C for A36. The highest weighted average dT' is 42,09 °C in A44, a similar value of 42,04 °C is in A36 and not far off A34 with 41,65 °C.

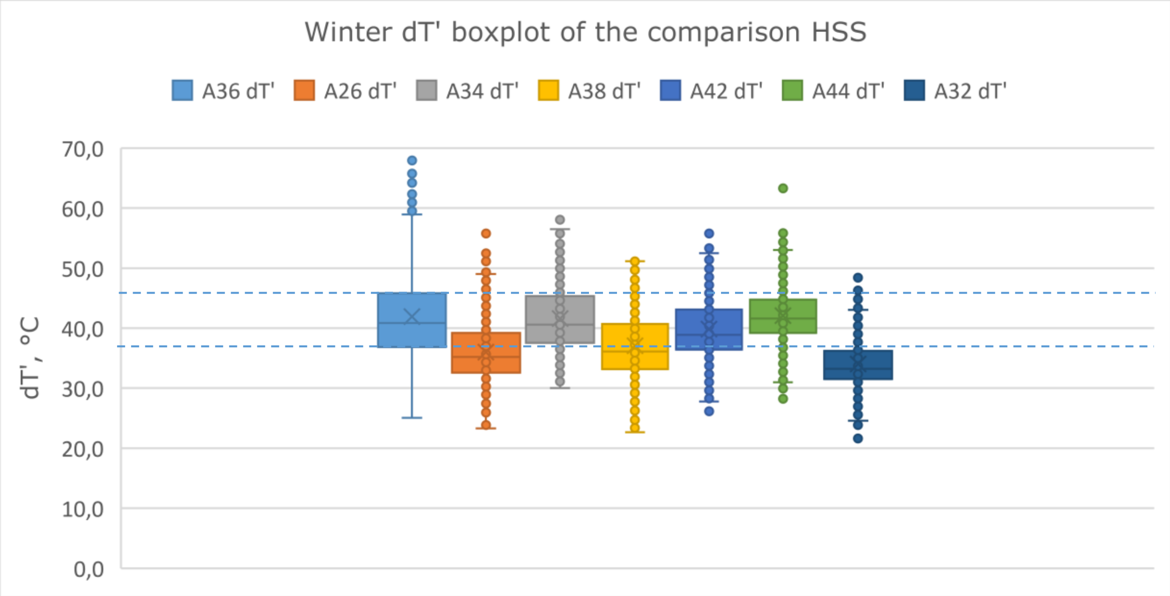


Figure 4.3. Winter dT' boxplots of comparison HSS

A36 dT’ is most responsive to changes in demand with an IQR of 9 and the largest difference between extremes of 33,9 °C. The most stable dT’ with an IQR of 4,7 and least performing in dT’ is A32 with 33,94 °C. Low dT’ IQR can be an indicator of less performing HSS, as this indicates a low response to changes in demand, but before conclusions, it has to be considered together with IQR of volume to understand the basis of dT’ IQR. Low dT’ IQR can indicate that a big proportion of the heat transfer is led by flow volume, not by the temperature difference. Ideally, a HSS dT’ would follow the demand curve and the flow volume would be very stable, i.e., HSS has a well-working control equipment, HEX and feedback loop from the secondary side’s temperature sensor(s) and can, by controlling flow changes smoothly, have high dT’ with low flow volume.

The second smallest dT’ IQR is in site A44 with 5,5. As seen in Table 4.5, A44 is the best performing in dT’ absolute numbers, thus having a small dT’ IQR means it has table dT’ at a higher level than other parallel HSS. Though A44 has smaller dT’ IQR and 3rd and median values higher than others, the weighted average dT’ is on bar with the test site A36s’ 2S-HSS. This is a reason why weighted average dT’ is used, more weight is given to dT’ values that are more relevant as the building was consuming and interacted with, and had more effect on the DHN. From this, is also clear that both higher and lower levels of dT’ can come at the expense of flow volume.

Moreover, Table 4.5 shows the IQR V, i.e., volume stability in a HSS heat transfer. This volume stability, together with high dT’ response to demand and efficient heat media use, seems to be one of the main pros of a 2S-HSS compared to standard 1S-HSS. Test site A36 has an IQR V of 0,17 m3/h, which is the smallest of the comparison HSS, thus the 2S-HSS has a smaller IQR V than regular 2S-HSS have. With IQR dT’ it is difficult to define, without adding other considerations, if a smaller or higher value is better, but with IQR V it is clear that smaller values are preferred, especially if the high extreme is also lower. For example, this can mean that DHC can use heat meters with smaller nominal flow volumes.

Figure 4.4 depicts the flow volumes for the comparison HSS. Though the sites have similar demand and peak demand (see Table 4.3), the flow volumes and IQR V differ greatly between them. Furthermore, it is interesting how the best performers regarding dT’ are performing in flow characteristics.

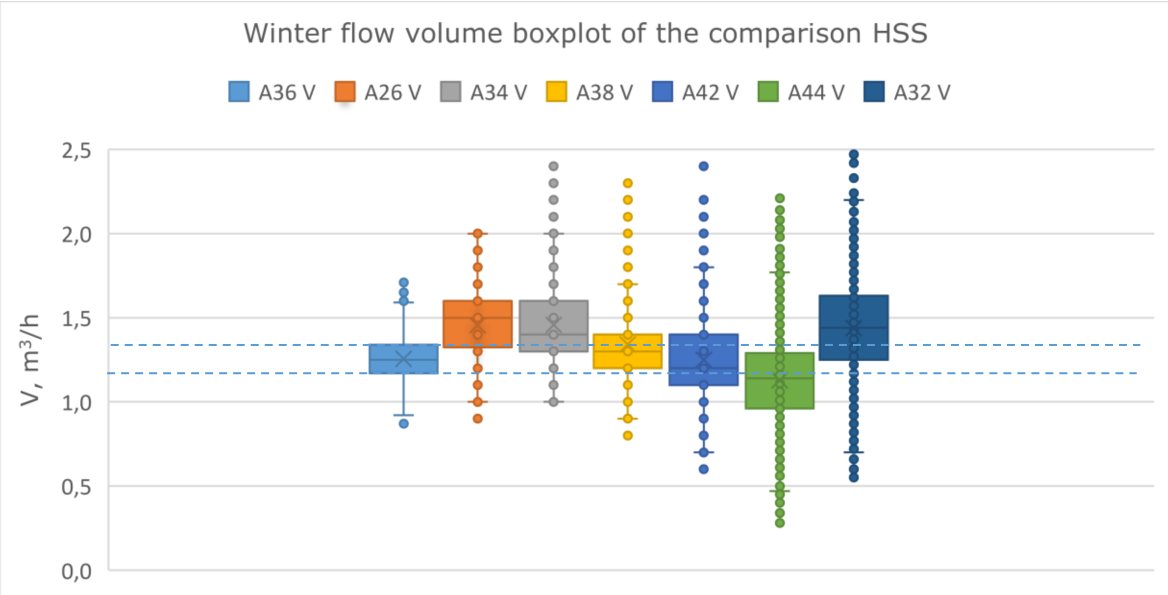


Figure 4.4. Winter flow volume boxplots of comparison HSS

It is seen from Figure 4.4 and Table 4.6 that the test site A36 2S-HSS has a smaller variation in flow volume than 1S-HSS has. Other best performance 1S-HSS, e.g., A34 and A44, have an IQR V of 0,3 m^3/h and 0,33 m^3/h respectively, these are 1,76- and 1,94-times higher values. Thus, 2S-HSS gives a volume demand predictability of approx. 1,85 times higher than 1S-HSS. Pro of 1S-HSS can be the lower total amount of volume in a longer period, as is the case for A44 (see Table 4.3) with a total volume over the course of the year 2021 being 1,45 times less than for the 2S-HSS. During winter this difference is not so pronounced, being 1,1 times the total flow difference.

2S-HSS has a small difference between extremes of 0,67, and 1S-HSS vary from 0,8 to 1,5 with high fluctuations in the flow volume. 75% of flow volume is below 1,34 m^3/h, only lower value is in site A44 with 75% of values being below 1,29 m^3/h.

Table 4.6. Flow volume median and quartiles

Site	1st quartile V, m^3/h	3rd quartile V, m^3/h	Median V, m^3/h	Difference between extremes
A36	1,17	1,34	1,25	0,67
A26	1,37	1,60	1,50	1

A32	1,25	1,63	1,44	1,5
A34	1,30	1,60	1,40	1
A38	1,20	1,40	1,30	0,8
A42	1,10	1,40	1,20	1,1
A44	0,96	1,29	1,14	1,3

Below parameters for an average HSS on the test site pipeline are given. A_aver is a HSS that comprises 3 HSSs that are connected to the pipeline before the 2S-HSS. A_aver is the average of parameters from sites A38, A42 and A44. This approach enables to get a broader view of how a well-performing average 1S-HSS would compare against 2S-HSS by averaging out the differences in these HSS to look at these parameters as one and compare them to the test site.

Table 4.7 shows the parameters for site A_aver.

Table 4.7. Parameters of fictional HSS A_aver

Site	MWh/ m3	dT'/ T1	T1, °C	dT', °C	IQR dT', °C	IQR V, m³/h	Volume SUM
A_aver	0,0457	0,4801	82,61	39,65	6,59	0,28	2676,66
	1st quartile dT', °C	**3rd quartile dT', °C**	**Median dT', °C**	**1st quartile V, m³/h**	**3rd quartile V, m³/h**	**Median V, m³/h**	**Difference between extremes**
A_aver	36,26	42,86	38,88	1,09	1,36	1,21	1,07

When comparing test site A36 with the A_aver it can be seen that the 2S-HSS would have beneficial performance characteristics, like a couple of degrees better dT' and higher dT'/T1 and MWh/m3 values. This with the former analysis makes it clear that 2S-HSS would be beneficial to use in Tallinn DHN if proper precautions are followed to keep the 2S-HEX clean. Volume smoothness is a characteristic of 2S-HSS, as can be seen in Figure 4.5, that helps a DHN company better predict pumping needs, pressure drop in the HSS and thus the pressures in the network and do less over pumping.

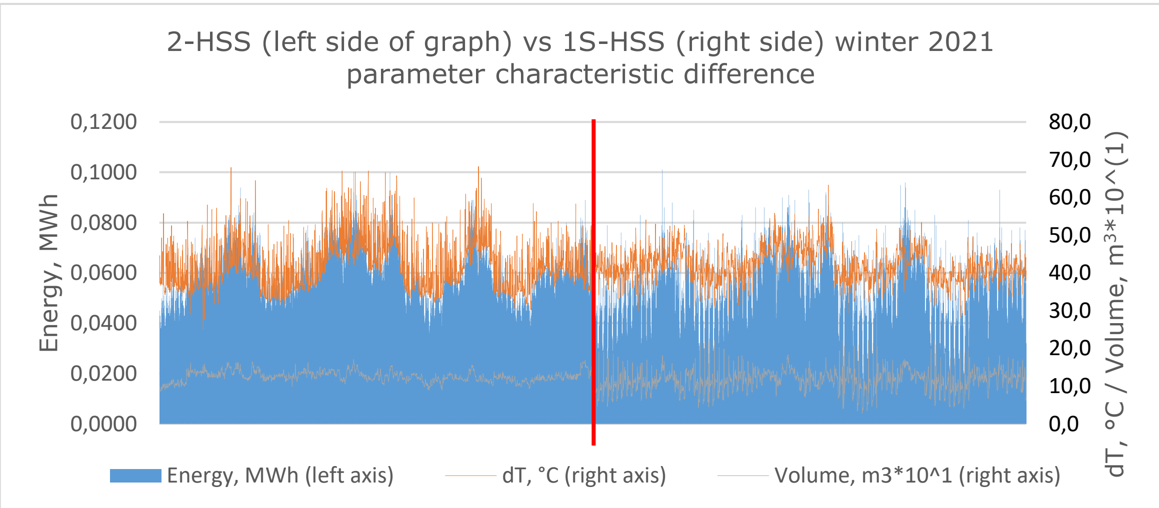


Figure 4.5. 2S-HSS vs 1S-HSS winter parameter characteristic difference

5 Parameter improvement possibilities for buildings with below-average parameters in Tallinn, considering the test site's HSS

According to Utilitas Tallinn, the DH operator of Tallinn, it has approximately 4200 buildings in its heating portfolio. Tallinn DHN is supplied by 3 biomass CHP plants, 1 waste incineration CHP, 3 large boiler houses, 11 smaller boiler houses and 2 solar parks. At the beginning of 2021, DH was supplied by 470 km of DHN. Every year, 10-15 km of pipework is either reconstructed or built [46]. A large part of DHN has been replaced, and 54% of DHN is either reconstructed or new piping. Tallinn is using pre-insulated piping and lowering the supply temperatures [47]. The highest temperature, according to supply temperature data, that is fed to the network, is 100 °C, in 2019 it was still at 118 °C.
It is clear, that the Tallinn DHN is in the process of moving toward 4 gen DHN. This is also suggested by the research [9] and that the technical improvement potential exists [3]. Figure 5.1 shows Tallinn DHN and its supply points. Not shown on the map, between the Central and Lääne district, the Spordi boiler house also exists and balances the flows between the Central and Lääne districts. On this DHN scale, there is a large potential for savings hidden on the consumer side.

Figure 5.1. Tallinn District heating Network [3]

To date, temperature decrease has been possible due to old HSS being well over-dimensioned. This might not be the case moving below supply temperatures of 100 °C. Getting consumers ready for the 4G network means looking into the future and making decisions now. Consumers need new HSS and these HSS need to be at levels that can accommodate lower temperatures in the future, without making sacrifices today. This is true both for existing and new customers.

A variety of parameters are tracked in the DHN, but the ones a consumer has the most effect on are the temperature and flow volume. It is then important to understand how HSS improvement would have an effect on a larger scale. The table below shows the main consumer parameters of Tallinn.

Table 5.1. Tallinn's average parameters for the 2021 winter months

T1, °C	**Weighted dT', °C**	**V, m³**	**dT'/T1**	**MWh/m³**
83,39	36,49	4795	0,450	0,0433

Knowing the parameters and having analysed the effect of changing an old HSS to a new one, it is possible to estimate what the potential effect on the total consumer side parameters, of changing a large number of HSS, would be. For that, two cases are presented. Test HSS is well suited for the basis of a new HSS in the scenarios, as this HSS has above average parameter values (see A36 in Table 4.5) and analysis showed promising results for parameter improvement.

At the time of estimation, the heating system configuration and heating graph data are not available. Thus, it is not possible to assess in how many buildings it is not advisable to install a 2S-HSS due to too high heating graphs and in how many buildings the dT' cannot be reduced due to high heating graphs. This can be assessed on a case-by-case basis and does not affect the current assessment. It must be considered when a large-scale installation would be undertaken.

5.1 Cases for low parameter HSSs improvement in Tallinn DHN

Consumers' energy efficiency is key to transition towards 4G DH [48]. DHC should remote monitor customers' substations, possess analytical tools to draw meaningful conclusions, react accordingly and be proactive in the approach of optimising DHN [49], that the customers are an integral part. As a start point, 4250 measuring points were considered, 113 had either a missing contracted load or parameter data. Thus, starting point for case 1 and case 2, before criteria, are the 4137 measuring points.

Assumption 1 is that the low parameter HSS parameter level can be increased when a new HSS installed. Assumption 2 is that the parameter levels achieved with the new HSS correspond to the level of the tested HSS. Assumption 3 is that all other HSSs stay at the same parameter level as they were.

The average dT’ for the winter months of 2021 in Tallinn DHN was 37,52 °C. Comparison level for heat media usage efficiency is chosen at 35 °C, i.e., HSS with 2021 winter months’ dT’ < 35 °C will be changed to new HSS. To ensure the assessment reflects a real-life scenario, extra criteria are, the T1 > 79 °C and total demand for the winter months > 50 MWh. Latter is necessary to filter out HSS with a small effect on the overall DHN parameter and concentrate on the ones that have a larger effect. Last but not least, only HSS with contracted DHW load > 150 kW are considered in case 1. The assumptions for case 2 are the same as for case 1. The difference is that case 2 is not limited to above 150 kW DHW contracted load, all DHW HSS that meet the other criteria are considered.

Values in Table 5.2 reflect the number of HSSs that meet different criteria and Table 5.3 reflects the situation before and after the HSSs have been changed. Parameters are calculated from the test site’s measured heat media usage efficiencies, i.e., the temperature difference is calculated from T1 of the HSS that is being changed, using the test site’s parameter dT’/T1 of 0,5208 and flow volume is calculated from demand, knowing test site’s Q/V is 0,0484 MWh/m3.

Table 5.2. Nr of HSS in the winter months of 2021 according to different criteria in Tallinn DHN

	Case 1	**Case 2**
Nr of measuring points	4137	4137
DHW	2362	3345
dT' < 42 °C	1528	2355
dT' < 35 °C	468	936
T1 > 79 °C	447	864
Q > 50 MWh	433	762

Of 4137 measuring points where different case criteria were applied, case 1 has 433 and case 2 has 762 low parameter HSS.

Table 5.3. Winter months parameter improvement for low parameter HSS in the example cases in Tallinn DHN

Criteria in Table 5.2	**Case 1**	**Case 2**
Old situation		
dT'	30,10	29,53
dT'/T1	0,360	0,354
MWh/m^3	0,0345	0,0339
Q, MWh	135 175	184 050
V, m^3	4 068 147	5 619 590
New situation		
dT' of test HSS	42,04	42,04
V, m^3	2 792 873	3 802 686
dT'	43,56	43,46
Parameter improvement of the old HSS		
dT' increase, °C	13,46	13,93
V, m^3 decrease	1 275 274	1 816 904

Values in Table 5.3 show that when all HSS in case 1 would be replaced by HSS with test HSS heat media usage efficiency, the resulting dT' average increase for winter months would be 13,46 °C and total flow volume decrease of 1,28 million m3, i.e., 31%. The resulting values for case 2 are 13,93 °C and 1,82 million m3. Data and calculation table in Appendix nr 2 – Pictures and data of the HSS.

Table 5.4. Tallinn DHN's winter HSS parameter change after installing new HSS as per cases

Old situation in Table 5.1	**New situation Tallinn DHN**			
	Weighted dT', °C	**V, m3**	**dT'/T1**	**MWh/m3**
Case 1	39,24	4487	0,467	0,0448
Case 2	40,49	4356	0,48	0,046

Case results show that the low performing HSS affect Tallinn's DHN HSS average parameters for the winter months. These HSSs are 10% of all measuring points and 20% of the total winter months' flow volume though HSS of almost 20 million m3. After case 1, these HSS would be 15% of the total winter flow volume. The primary temperature difference dT' would be improved approx. 2,75 °C. After case 2, the dT' improvement is more pronounced at 4 °C.

With yearly analysis, the T1 was chosen at 70 °C, dT' at 30 °C, and total demand above 100 MWh/y. Tallinn DHN's average T1 of 2021 for HSS was 78 °C. It is estimated that conventional DH systems can achieve an annual T1 of 69 ° C [50]

Table 5.5. Tallinn DHN's yearly HSS parameter changes after installing new HSS as per cases

Old situation Tallinn DHN				
	dT', °C	**V, m3**	**dT'/T1**	**MWh/m3**
	33,75	11374	0,438	0,0396
New situation Tallinn DHN				
Case 1	35,79	10751	0,452	0,0408
Case 2	36,79	10465	0,466	0,042

Increased dT' and flow volume decrease have large monetary implications for the DHC. As case 2 implies changing 80% more HSS, case 1 might be a more reasonable option. This parameter improvement will need further monetary assessment that is not covered in this thesis. Overall, both winter and yearly results show that when a good criteria basis is chosen for the target group of HSS and well-functioning new HSS are used, a HSS replacing program could be developed for the HSS in Tallinn DHN that would be economically viable.

Discussion

The comparison results could be improved by having more past temperature data about the test site, not only heat meter data. The test site's temperature data accuracy could be further improved by using only immersed temperature sensors. With more temperature data, a more in-depth comparison between old and new HSS could be performed. The same goes for comparison sites.

In the comparison of old vs new HSS, the flow volume is much less with the new one. In the comparison of 2S-HSS vs 1S-HSS, 2S-HSS has a more stable flow and 1S-HSS has a higher peak flow. The pumping power is directly proportional to the power of three of the flow volume rate. The next steps would be to analyse the impact on pumping power and energy cost related to pumping with these designs. An important thing to weigh in this comparison would be if the stable flow volume and potentially higher total flow volume of 2S-HSS are more beneficial from the DHC perspective than the highly fluctuating, but with lower total volume, 1S-HSS.

From the primary side perspective, the flow and pressure control must be stable and predictable. HEX are often deliberately over-dimensioned to take into account the future fouling of HEX, commonly used is a 20% margin. If DHC reduces HSS calculated T1 from 100 °C to 85 °C, assuming the secondary side is kept constant at for example 50/70 °C, then the initial over-dimensioning of the HEX would be 100 %. Initially, it will bring higher dT values, which is favourable, but in the long run, as the T1 is reduced, the dT will begin to decrease to meet the design calculation values. As the future T1 values are taken into account long before the T1 meets the calculation values, the dT is predictable, favourable and will meet the dT requirements of a DHC today and in the future. Thus, reducing HEX primary calculation parameters is necessary to achieve a temperature target in the future. An exact target depends on the DHC policy.

With proper dimensioning tools, the desired future parameters can be ensured and on the other hand, the exact dimensioning of HEX is not so critical in the heating HEX as the processes are slow and modern control equipment can ensure the desired temperature parameters. It is of utmost importance that when new parameters are introduced to the DHC's technical calculation criteria that the responsible employees are thorough when looking into the HEX calculation, making sure the HEX is not under-dimensioned, but at the same time that the at least the secondary side would have turbulent flow characteristics.

DHC should drive the innovation and make sure all of its customers are part of it. Over-dimensioning is an economic issue, rather than a problem for the DHN. DHCs make large investments into infrastructure and to get the best out of future DHN and heat sources connected to it, the customers ought to be on board and make investments into their equipment as well. When thinking about the price increase of HSS due to over-dimensioning, it should be considered that HSS manufacturers use a limited number of standard HEX, e.g., HEX with plates of 20, 40, 60 etc., not all the different HEX from HEX manufacturer’s nomenclature. Thus, lowering calculation T1 does not have a linear effect on the price.

It is important to accelerate both the heating system renovation and installing of new HSS. 2S-HSS can have a part in it, but this is a consideration of if stable flow volume gives enough incentive for a DHC. Replacing old HSS also gives way to lower calculation temperature, more precise control of HSS and demand-side management capabilities that support DHC’s efforts from other angles.

SUMMARY

Oevelen et al. well formulated the role of temperatures in the overall efficiency of DHN [1]. Averfalk H et al. further underline the possibility of a greater energy mix in the DHN with lower temperatures [2]. Latõšov et al. showed there are technical possibilities to decrease network temperatures in Tallinn's DHN [3]. Averfalk and Werner suggested the future NTU values of HEX are between 6-8 [6]. Guelpa et al. emphasised the importance of mass flows in the system [7]. Volkova et al. showed that future improvements in Tallinn DHN should be focused on reducing supply and return temperatures [11]. Werner and Frederiksen graphically show that 2S-HSS have a better primary temperature difference dT' than parallel design [4].

Literature shows the importance of low temperatures, goes in-depth about fault detection, what the faults may be, control systems, demand-side management etc., but does not address replacing an old HSS. Heating substations have many design possibilities. A 2-stage heating (2S-HSS) substation design is not used in Estonia due to high Calcium concentration in the mains water and the domestic hot water (DHW). It raises the question of whether this direction should be reconsidered, what to bear in mind when implementing 2S-HSS and what is the effect of replacing an old HSS.

This thesis addresses this gap and comprises the theoretical basis of heat exchangers (HEX) and the practical part consists of the test site's old vs new HSS parameter analysis, HSS comparison site parameter analysis and finally a broader look is taken on how a low parameter HSS replacement scheme would affect HSS average parameters in Tallinn's DHN.

Analysed data, site comparison and Tallinn's delta improvement show a promising outlook in using 2-stage heating substations (2S-HSS) for consumers with larger contracted domestic hot water heat loads. The test site's contracted DHW load was 151 kW. Analysis of HSS T2 and H-HEX T2 correlation shows that this DHW contracted load can be taken as the minimal level for 2S-HSS implementation. Moreover, less DHW usage would have had an unfavourable effect on the HSS T2. Already, the average HSS T2 was a bit higher than H-HEX T2, but during DHW consumption hours, 2S-HSS performed well and HSS T2 was considerably lower than H-HEX T2 (up to 45 °C lower in a measuring interval of 1 minute and on average 5,2 °C for positive values).

An important parameter improvement is a very smooth volume graph, even compared to similar dT' HSS, and thus a predictable pressure drop over a HSS. 2S-HSS dT' responds very well to demand and uses heat media efficiently by having the year 2021 winter weighted average dT' of 42,04 °C. Other efficiency measures are also above Tallinn DHN's averages, as a load to flow volume ratio of 0,0484 MWh/m3 and dT'/T1 ratio of 0,502.

2S-HSS is easier to put together and needs fewer bends in piping, making it more cost-effective, at least on the production side. 2S-HSS could be used in Tallinn and wider in Estonian DHN, but not in every building. The main things to consider are the DHW demand, cleaning regularity of HEX and the temperature graphs in the heating secondary side. 2S-HSS should be used with lower temperature heating systems to avoid calcium carbonate formation in the 2S-HEX pre-heating part. The test site's heating side temperature graph was considerably low at 43/63. From opening the DHW-HEX, no calcium carbonate, i.e., the lime-scale formation was detected, but Ferrum concentration was concerning. The hot water side of the DHW-HEX ought to be cleaned with a regular interval of 1- 1,5 years. This recommendation holds for areas where a lot of Ferrum or its particles may be found in the water coming from the mains. The reason for Ferrum can be rusty mains piping systems.

According to Mašatin et al. 2018, the main obstacle to moving toward the 4G network is the consumers. To reach 4G DHN in the future, DHC should act now and take decisive actions regarding the HSS and consumers. For example, Tallinn DHN could decrease its H-HEX T1 calculation criteria from 100 to 85 °C. Calculating for HEX values of tomorrow yields high NTU values, up to 9,55 in the example, for temperatures of today.

Lowering calculation temperatures would give the possibility for the DHC to gradually decrease the T1 temperature over the years as more and more HSS parameters comply with the lower DHN temperatures. As HSS are only a part of the temperatures story, DHN ought to work together with Building Associations to recommend radiator systems with lower temperatures as well.

Two cases were presented for old HSS replacement program. How to implement and where funding comes from were not in the scope of this work. In case nr 1, 433 low performing HSS would be replaced and in case nr 2, 762. The HSS to be replaced were chosen as the least performing by dT' in the DHN. Case nr 1 assumes, the HSSs to be replaced have a contracted DHW load of at least 150 kW. Replacing old HSS with new HSS that have the test site's parameters, could improve DHN winter months dT' by 2,75 °C and yearly dT' by 2,04 °C for case nr 1; and 4 °C and 3,04 °C for case nr 2, 2021 is taken as the comparison year. Compared to a fictional HSS, created from other similar sites, the test site's dT' performed approx. 3 °C better during the winter months.

Results show the 2S-HSS has good parameters, especially the stable flow characteristic. A large scale HSS replacement scheme might be economically viable when coupled with other products like DSM. Economic assessment is not in the scope of the thesis and can be a part of future studies. 2S-HSS could be used in the Estonian market when the right use cases are chosen for it, as discussed above and in the thesis.

Kokkuvõte

Oevelen et al. sõnastasid hästi temperatuuride rolli kaugküttevõrgu (KKV) üldises efektiivsuses [1]. Averfalk H et al. rõhutavad võimalust, et madalamate temperatuuridega on KKV-s võimalik suurem energialiikide kombinatsioon [2]. Latõšov et al. näitasid, et Tallinna KKV-s on tehnilisi võimalusi võrgutemperatuuri alandamiseks [3]. Averfalk ja Werner tõid välja, et soojusvaheti (SV) tulevased NTU väärtused on vahemikus 6-8 [6]. Guelpa et al. rõhutas vooluhulkade tähtsust süsteemis [7]. Volkova et al. näitasid, et Tallinn KKV tulevased parendused peaksid keskenduma peale- ja tagasivoolu temperatuuride vähendamisele [11]. Werner ja Frederiksen näitasid graafiliselt, et kaheastmelise soojussõlme (2A-SS) primaarpoole temperatuuride vahe dT′ on suurem kui parelleeldisaini puhul [4].

Kirjandus näitab madalate temperatuuride tähtsust, käsitleb põhjalikult rikete tuvastamist, tõrkeid, juhtimissüsteeme, nõudluse juhtimist jne, kuid ei käsitle vana soojussõlme (SS) väljavahetamist. SS-l on palju disini võimlausi. Eestis ei kasutata kaheastmelisi soojussõlmi (2A-SS), sest tarbe- ja sooja vee kaltsiumi sisaldus on kõrge. See tõstatab küsimuse, kas see suund tuleks üle vaadata, mida 2A-SS rakendamisel silmas pidada ja milline on vana SS asendamise mõju.

Lõputöö täidab selle lünga, koosnedes soojusvahetite teoreetilisest alusest ning praktiline osa koosneb katseobjekti vana ja uue SS parameetrite analüüsist, võrdlusobjektide parameetrite analüüsist ja viimases osas vaadeldakse laiemalt, mis mõju oleks Tallinna KKV-s kõige kehvemate parameetritega soojussõlme asendamisel.

Analüüsitud andmed, objektide võrdlus ja Tallinna delta paranemine näitavad paljulubavat väljavaadet kasutada 2-astmelisi soojussõlmi suuremate soojavee soojuskoormustega tarbijate puhul. Katseobjekti lepinguline sooja tarbevee (STV) koormus oli 151 kW. SS T2 ja kütte SV T2 korrelatsiooni analüüs näitab, et seda STV lepingulist koormust võib pidada 2A-SS rakendamise minimaalseks tasemeks. Lisaks, väiksem STV koormus oleks parameetritele negatiivset mõju avaldanud. Juba praegu oli keskmine SS T2 veidi kõrgem kui kütte SV T2, kuid STV tarbimistundidel toimis 2A-SS hästi ja SS T2 oli tunduvalt madalam kui kütte SV T2 (kuni 45 °C madalam mõõteintervalliga 1 minut ja keskmiselt 5,2 °C positiivsete väärtuste puhul).

Oluline parameetrite paranemine on väga ühtlane vooluhulk, isegi võrreldes sarnase dT' SS-ga, ja seega prognoositav rõhulang SS-s. 2A-SS dT' reageerib nõudlusele väga hästi ja tagab soojuskandja tõhusa kasutuse, 2021. aasta talvekuude kaalutud keskmise dT' oli 42,04 °C. Ka teised energikandja efektiivse kasutuse näitajad ületavad Tallinna KKV keskmisi näitajaid, koormuse ja vooluhulga suhe on 0,0484 MWh/m3 ja dT'/T1 suhe 0,502.

2A-SS on lihtsam kokku panna ja vajab vähem torude painutamist, muutes selle kulutõhusamaks, vähemalt tootmise poolel. 2A-SS on võimalik kasutada Tallinna ja laiemalt Eesti KKV-des, kuid mitte igas hoones. Peamised asjad, mida arvesse võtta on STV nõudlus, SV-i regulaarne puhastamine ja sekundaarpoole temperatuurigraafikud. Kaltsiumkarbonaadi (katlakivi) tekke vältimiseks 2A-SV eelsoojenduse astmes on soovituslik 2A-SS-i kasutada madalama temperatuurigraafikuga küttesüsteemides. Katseobjekti küttegraafik oli võrdlemisi madal 43/63. Tarbevee soojusvaheti avamisel kaltsiumkarbonaadi ladestumise märke ei tuvastatud, aga raua kontsentratsioon soojusvahetuspindadel oli suur. STV-SV kuuma vee poolt tuleb puhastada regulaarse intervalliga 1-1,5 aasta tagant. See soovitus kehtib piirkondadele, kus veevõrgust tulevast veest võib olla palju rauda või selle osakesi. Raua põhjuseks võivad olla roostes võrgutorustikud.

Mašatin et al. 2018 andmetel on 4G KKV suunas liikumise peamiseks takistuseks tarbijad. Tulevikus 4G KKV-ni jõudmiseks peaks võrguettevõtted täna tegutsema ja otsustama kuidas selles pildis tarbijapaigaldisetaga tegeleda. Näiteks saaks Tallinna KKV oma kütte SV-de T1 arvutuskriteeriume 100-lt 85 °C-le alandada. SV-de tulevikuväärtustele arvutamine tähendab kõrgeid NTU väärtuseid, näidisarvutuses kuni 9,55.

Arvutustemperatuuride alandamine annaks kaugkütte ettevõttele võimaluse T1 temperatuuri aastate jooksul järk-järgult vähendada, sest üha suurema hulga SS-de parameetrid hakkavad vastama madalamatele KKV temperatuuridele. Kuna SS-d on vaid osa temperatuuride langetamsiest, peaks kaugkütte ettevõtted tegema koostööd ehitusliitudega, et soovitada ka madalamate temperatuuridega radiaatori süsteeme.

Vanade SS-de asendusprogrammi jaoks esitati kaks juhtumit. Töö raames ei uuritud kuidas seda rakendada ja kust rahastus tuleb. Juhtumil nr 1 asendataks 433 madalate parameetritega SS ja juhtumil nr 2 762. KKV-s asendatavateks soojussõlmedeks valiti kõige madalama dT’ väärtusega soojussõlmed. Juhtumi nr 1 eeldus on, et asendatavate SS-de lepinguline STV koormus on vähemalt 150 kW. Vanade SS-de asendamine uutega, millel on testobjekti parameetrid, parandaks juhtumi nr 1 puhul KKV talvekuude dT’ 2,75 °C ja aastast dT’ 2,04 °C; juhtumi nr 2 puhul 4 °C ja 3,04 °C, võrdlusaastaks on 2021. Võrreldes fiktiivse SS-ga, mis on loodud võrdlusobjektide keskmisena, oli katseobjekti SS-e dT’ talvekuudel umbes 3 °C parem.

Tulemused näitavad, et 2A-SS-l on head parameetrid ja eriti ühtlane voolukulk. Suuremahuline SS-de asendusprogramm võib olla majanduslikult elujõuline, kui seda kombineeritakse teiste toodetega, nt DSM. Majanduslik hinnang ei olnud antud töö mahus ja saab olla osa tulevastest uuringutest. Nagu lõputöös ja eespool mainitud, siis 2A-SS saab Eestis kasutada kui valida õiged kasutuskohad.

LIST OF REFERENCES

[1] T. V. Oevelen, D. Vanhoudt and R. Salenbien, "Evaluation of the return temperature reduction potential of optimized substation control," *Energy Procedia,* vol. 149, pp. 206-215, 2018.

[2] H. Averfalk, "Low-Temperature District Heating Implementation Guidebook," IEA DHC, 2021.

[3] E. Latõšov, A. Volkova, A. Hlebnikov and A. Siirde, "Technical improvement potential of large district heating network: application to the Case of Tallinn, Estonia," *Energy Procedia,* vol. 179, pp. 337-344, 2018.

[4] F. S. and W. S., District Heating and Cooling, 1 ed., The authors, Svensk Fjärrvärme and Studentlitteratur, 2013, pp. 375 - 378; 390.

[5] Y. A. Cengel, Heat Transfer; A practical Approach, McGraw-Hill, 2002.

[6] H. Averfalk and S. Werner, "Essential improvements in future district heating systems," *Energy Procedia,* vol. 116, pp. 217-225, 2017.

[7] E. Guelpa, "Impact of thermal masses on the peak load in district heating systems," *Energy,* vol. 214, 2021.

[8] H. Gadd and S. Werner, "Heat load pattern in district heating substations," *Applied Energy,* no. 108, pp. 176-173, 2013.

[9] V. Mašatin, "Doctoral Thesis: Obstacles for Implementation of 4th Generation District Heating for Large Scale Networks," TTÜ Press, Tallinn, 2018.

[10] H. Gadd and S. Werner, "Fault detection in district heating substations," *Applied Energy,* vol. 157, pp. 51-59, 2015.

[11] A. Volkova, V. Mašatin and A. Siirde, "Methodology for evaluating the transition process dynamics towards 4th generation district heating networks," *Energy,* vol. 150, pp. 253-261, 2018.

[12] F. P. Incropera, D. P. Deqitt, T. L. Bergman and A. S. Lavine, Fundamentals of Heat and Mass Transfer, John Wiley & Sons, 2006.

[13] SWEP, Refigeration handbook, SWEP.

[14] Alfa Laval, Alfa Laval Fluids Handbook, Alfa Laval.

[15] Estonian Power and Heat Association, Soojussõlmed, juhised ja eeskirjad; "Heating substations, Instructions and Rules", vol. IV täiendatud trükk, 2019.

[16] D. Prits, *Author's personal gallery/portfolio.*

[17] J. E. V. Rebollar, E. Himpe and A. Janssens, "PERFORMANCE ASSESSMENT OF DISTRICT HEATING SUBSTATIONS BASED ON DYNAMIC SIMULATIONS," in *The 14th International Symposium on District Heating and Cooling*, Stockholm, 2014.

[18] CeteTherm, "Webselect heating substation dimensioning program," 2022. [Online]. Available: webselect.nibe.se.

[19] A. O'Dwyer, Handbook of PI and PID Controller Tuning Rules, 3rd edition, London: Imperial College Press, 2009.

[20] Omega, "Omega, what is a PID controller," [Online]. Available: https://www.omega.co.uk/prodinfo/pid-controllers.html#:~:text=A%20PID%20controller%20is%20an,most%20accurate%20and%20stable%20controller.. [Accessed 05 2022].

[21] J. Yuan, K. Huang, Z. Han, C. Wang, S. Lu and Z. Zhou, "Evaluation of the operation data for improving the prediction accuracy of heating parameteres in heating substations," *Energy,* no. 238, 2022.

[22] Y. Wang, ShijunYou and H. Zhang, "Operation stability analysis of district heating substation from the control perspective," *Energy and Buildings,* vol. 154, pp. 373-390, 2017.

[23] S. Månsson, P.-O. J. Kallioniemi, K. Sernhed and M. Thern, "A machine learning approach to fault detection in district heating substations," *Energy Procedia,* vol. 149, pp. 226-235, 2018.

[24] E. Gulpa and V. Verde, "Automatic fouling detection in district heating substations: Methodology and tests," *Applied Energy,* no. 258, 2020.

[25] E. Davoudi and B. Vaferi, "Applying artificial neural networks for systematic estimation of degree of fouling in heat exchangers," *Chemical Engineering Research and Design,* vol. 130, pp. 138-153, 2018.

[26] R. Toffanin, V. Curti and M. C.Barbato, "Impact of Legionella regulation on a 4th generation district heating substation energy use and cost: the case of a Swiss single-family household," *Energy,* vol. 228, 2021.

[27] E. Chibowski and A. Szcześ, "Magnetic water treatment–A review of the latest approaches," *Chemosphere,* vol. 203, pp. 54-67, 2018.

[28] J. Coey, "Magnetic water treatment-how might it work?," *Philosophical Magazine,* vol. 92, no. 31, pp. 3857-3865, 2012.

[29] S. Aliu, O. Amoo, F. I. Alao and S. Ajadi, "Mechanisms of heat transfer and boundary layers," in *Applications of Heat, Mass and Fluid Boundary Layers*, Woodhead Publishing Series in Energy, 2020, pp. 23-53.

[30] J. Zhang, X. Zhu, M. E.Mondejar and F. Haglind, "A review of heat transfer enhancement techniques in plate heat exchangers," *Renewable and Sustainable Energy Reviews,* vol. 101, pp. 305-328, 2019.

[31] PJ Heat Exchanger Services, "Former CeteTherm heat exchangers in the Alfa Laval nomenclature," [Online]. Available: https://www.pjheatex.co.uk/product-category/cetetherm-plate-heat-exchanger/. [Accessed 04 2022].

[32] Ouman, "Ouman products," [Online]. Available: https://ouman.fi/en/products/. [Accessed 03 2022].

[33] ModBus Organization , "modbus.org," 24 10 2006. [Online]. Available: https://modbus.org/docs/Modbus_Messaging_Implementation_Guide_V1_0b.pdf. [Accessed 03 2022].

[34] Ouman, "Ounet," Ouman, [Online]. Available: www.ounet.fi.

[35] Ouman, "Ouman temperature sensor product page," [Online]. Available: https://ouman.fi/en/products/temperature-measuring-sensors-and-room-units/. [Accessed 03 2022].

[36] Kampstrup, "Kamstrup Multical 66CDE technical description," [Online]. Available: https://www.multical.hu/upload/files/MC_66C_Technical_Description_5511-634_GB_Rev_C1.pdf. [Accessed 03 2022].

[37] Kamstrup, "Kamstrup products," 5 10 2021. [Online]. Available: https://koce1-kamstrup.ocecdn.oraclecloud.com/content/published/api/v1.1/assets/CONT0032F74AB4A948B7B15E933A7D40AF25/native/5810395_L1_GB.pdf?channelToken=ed241bbb18f444908a8fc9ed97ca5d5b. [Accessed 03 2022].

[38] W. Wu and U. Piomelli, "Effects od surface roughness on separating turbulent boundary layer," *Journal of Fluid Mechanics,* vol. 841, pp. 552-580, 2018.

[39] S. Farouq, S. Byttner and H. Gadd, "Towards understanding district heating substation behavior using robust first difference regression," *Energy Procedia,* vol. 149, pp. 236-245, 2018.

[40] V. Chipulis, R. Kuznetsov and E. Voloshin, "Remote Control of Heating System and Analysis of Energy Efficiency," *Advanced Materials Research,* October 2014.

[41] Y. Wang, S. You and H. Zhang, "Operation stability analysis of district heating substation from the control perspective," *Energy and Buildings,* vol. 154, pp. 373-390, 2017.

[42] "Appendix A Details of Boxplot Construction," *Studies in Environmental Science,* vol. 49, pp. 451-455, 1992.

[43] Google, "Google maps," [Online]. Available: https://www.google.com/maps/place/Astangu+36,+13519+Tallinn/@59.4033303,24.6311291,17z/data=!3m1!4b1!4m5!3m4!1s0x469295b5e320b873:0xbe32b27170ffe879!8m2!3d59.4033303!4d24.6333178. [Accessed 2022].

[44] The Republic of Estonia, Ministry of Economic Affairs and Communication, "Eesti Ehitusregister," [Online]. Available: www.ehr.ee. [Accessed 2022].

[45] Utilitas, *ArcGIS based Utilitas Geo info system,* 2022.

[46] Utilitas group, "Utilitas webpage," [Online]. Available: https://www.utilitas.ee/as-utilitas-tallinn/. [Accessed 04 2022].

[47] TalTech, "Development Plan of Tallinn's Unfied District Heating Network; "Tallinn ühte kaugküttevõrgu arengukava"," TalTech, Tallinn, 2020.

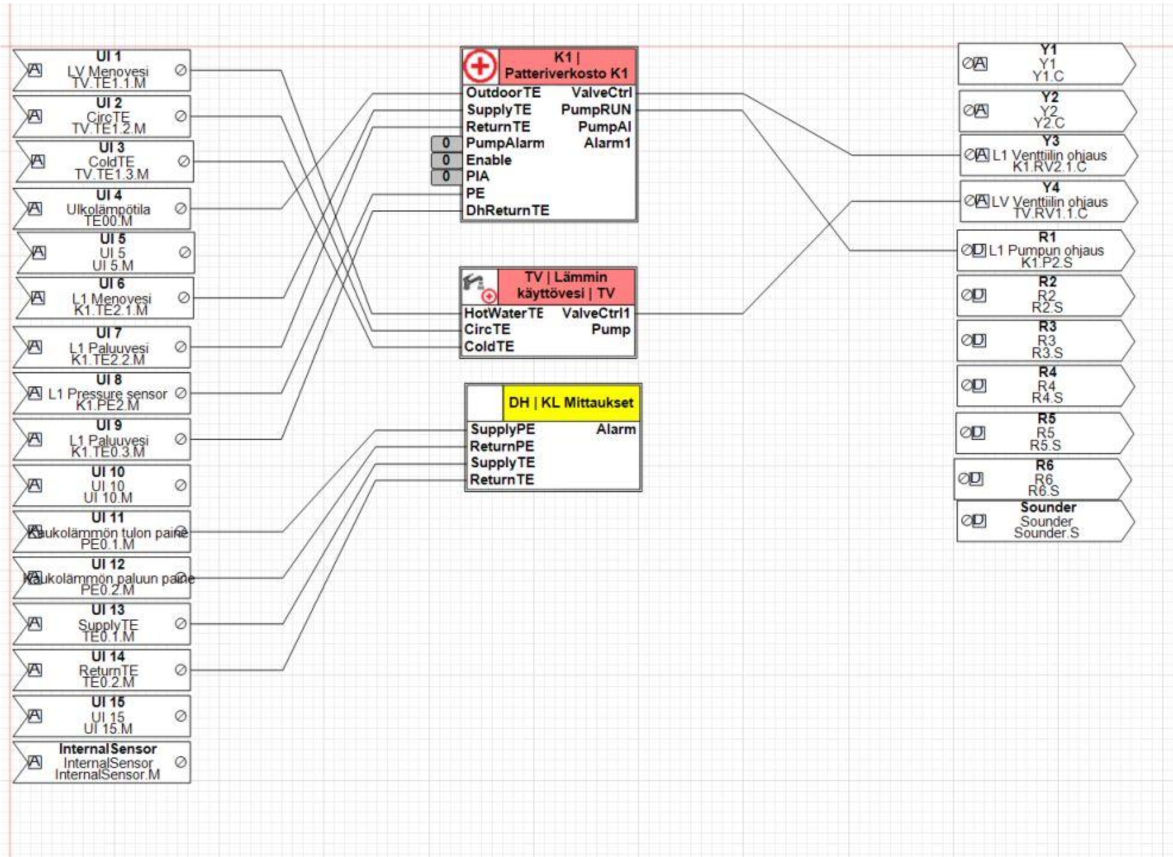
[48] J. Ziemele, N. Talcis, U. Osis and E. Dace, "A methodology for selecting a sustainable development strategy for connecting low heat density consumers to a district heating system by cascading of heat carriers," *Energy,* vol. 230, 2021.

[49] A. Garrido-Marijuan, O. Eguiarte, R. Garay-Martinez, M. Raud and I. hagu, "Lessons Learnt from Substation Inspection on Low Temperature District Heating Networks," in *The 9th Annual Edition of Sustainable Places (SP 2021)*, Rome, 2021.

[50] P. Gummérus, "Analys av konventionella abonnentcentraler i fjärrvärmesystem, "Analysis of conventional substations in district heating systems"," Chalmers Tekniska Högskola: Instutitionen för Energiteknik, Gäteborg, 1989.

APPENDICES

Appendix nr 1 - Wiring diagram for the MBA program



Appendix nr 2 – Pictures and data of the HSS.

Links will be active for 3 months after submission of the Thesis. If in the future one wishes to access the data, turn directly to the author of the Thesis.

Link to DHW HEX cutting pictures and videos

Link to pictures of A36 HSS

Link to A36 heat meter data for 2019 and 2021

Link to new HSS PQ modified temperature data

Link to new HSS raw data

Appendix nr 3 – Kamstrup Multical DataSheet

Approved measuring data

Approv. authority/standard		DS/EN 1434 and DIN/EN 1434

HEAT METER

Temperature range	θ	10°C...160°C
Differential range	Δθ	3K...150K

COOLING METER

Temperature range	θ	2°C...30°C
Differential range	Δθ	3K...20K

Accuracy	E_c	±(0.5 + Δθ min/Δθ) %
Temperature sensors		Pt500 - EN 60 751
Flow meter sizes	θp	0.6 m³/h...3000 m³/h
Environment class		A

Technical data

TEMPERATURE INPUTS T1, T2 AND T3

Temperature range	0°C...165°C
Differential range	0K...160K
Display resolution	0.01K
Sensor type	Pt500 - EN 60 751

FLOW METER INPUTS V1 AND V2

Input resistance	> 100 kΩ
Pulse ON (< 0.5 V)	> 0.5 msec.
Pulse OFF (> 2.0 V)	> 10 msec.
Pulse frequency	< 128 Hz
Integration frequency	< 1 Hz

MATERIAL CHARACTERISTICS

Calculator top	SAN
PCB casing	ABS
Connection unit	PP
Gaskets	Sarlink 3150 B
Wall bracket	PC+30% glass

TYPE APPROVALS

TS 27.01 062 TS 27.01 098

DS 2340 EN 1434

PTB 22.52 01.03 22.55 00.03

Complies with following standards	EN 1434, DS 2340, OIML R75, PTB
CE-mark	LVD and EN 50 081-1 and EN 50 082-1

GENERAL DATA

Accuracy, calculator	±(0.15 + 2/Δθ) %
Accuracy, sensors pair	±(0.4 + 4/Δθ) %
Voltage supply	3.65 VDC ±10%
Power consumpt. - idle	< 35µA excl. flow meter
Back-up battery -lifetime	½ AA lithium cell 20 years with wall mounting
Primary battery -lifetime	D-cell lithium, HiCap 10 years with wall mounting 8 years with compact mounting 5 years with 2 flow meters connected
Net supply	230 VAC +15/-30%, 48...52 Hz 24 VAC/DC ± 30%
Power absorbtion	< 1 W (1 VA)
Supply back-up	Integral SuperCap which eliminates operation stop due to power cuts up to 5 min.
Data output	Passive, isolated serial data Req: 300 Baud, Data: 1200 Baud Can be converted to RS232
Permanent memory	EEPROM
Display	LCD, 8+3 digits, 7 mm digit height
Optical IR head	EN 61 107

PULSE OUTPUT, CE AND CV

Max. voltage/power	30V/10 mA
Pulse duration	32 msec.

PULSE INPUT

Input A (< 0.5 Hz)	Pulse duration > 1 sec.
Input B (< 3.0 Hz)	Pulse duration > 0.15 sec.

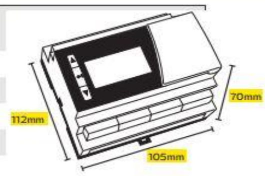
GENERAL

Ambient temperature	0°C...55°C
Storage temperature	-20°C...60°C
Protection class	IP 54
Weight	0.4 kg, excl. flow meter

Appendix nr 4 – MBA and M-Link datasheets

Technical information — OUFLEX M BA

Compact freely programmable automation unit



Dimensions	width 105 mm, height 112 mm, depth 70 mm DIN rail-mounted module casing, 6 modules.
Weight	0.28 kg
Protection class	IP 20
Operating temperature	0 °C...+50 °C
Storing temperature	-20 °C...+70 °C
Power supply	
Operating voltage	24 VAC-33VAC (50-60 Hz) or 20 – 48VDC
Power requirement 24VAC	9VA With the optional accessories (M-Link /GSM and external display) 12VA
Power requirement 24VDC	4W With the optional accessories (M-link/GSM and external display) 6.5W
Measurement inputs:	15 pcs, programmable
passive sensors (Inputs M1...M15) - NTC10:	Measurement channel accuracy in the measuring range -50 ... 130 ° C: Measurement channels 1-3 ±0.1 °C Measurement channels 4-15 ±0.1 °C between -20 °C...+120 °C, ±0.3 °C between -50 °C...-20 and ±0.2 °C between +120 ..130 °C
- NTC-20:	Measurement channels 1-3 ±0.1 °C Measurement channels 4-15 ±0.1 °C between 0 °C...-120 °C, ±0.7 °C between -50 °C...0 °C and ±0.2 °C between +120 °C...+130 °C
-NTC 1.8 and NTC 2.2:	±0.2 °C between -50°C...+100 °C, ±0.5 °C between +100 °C...+130 °C
-Ni1000LG/DIN:	+0,3 °C between -50 °C...+130 °C
-Pt1000:	+0,3 °C between -50 °C...+130 °C Also sensor tolerances and the effect of cables must be considered when calculating total accuracy.
Digital inputs (Inputs M1...M3)	Contact voltage 5 Vdc, Switching current 0.5 mA Transfer resistance max. 1,9 Ω (closed), min. 11 k Ω (open).
Active sensors (Inputs M4...M15)	Voltage measurement 0-10 V, meas. accuracy 0,5 % Current measurement 0/4...20mA, meas. accuracy 1,5 % .
Pulse inputs (Inputs M1...M3)	Minimum pulse length 30s
Analog outputs (Y1...Y4)	4 pcs. Output voltage range 0...10 V. Output current max 7 mA /output.
PWM output:	1 piece that works in parallel with the Y1 output . The open circuit voltage of 15V.Output current is max. 50 mA, when output voltage is 10V
Relay outputs	6 pcs relays normally open contacts, 230V, 5A max,
Data transfer connections	
RS-485 connections (A1, B1 and A2, B2)	2 pcs, not optoisolated (Modbus RTU master or 1 RTU slave) COM2 ja COM4.
RS-232	1 , support to the external display (Ouman LCD), connector COM1
RS-232	1 , support to the GSM modem and M-Link. NB! GSM modem and M-LInk can not be used simultaneously.
USB vonnector	1, Ouflex BA Tool online connection, COM5
MicroSD memory card	Memory card is not included in the delivery. Technical requirements to microSD memory card: Standard micro SDHC, UHS, Capacity 512 MB ...32 GB, File system FAT 32, Class: 4...10+
Freely programmable	Yes, with Ouman's Ouflex BA Tool
Ouman ACCESS security solution	yes with M-Link
Options	
M-Link	M-Link network adapter provides Modbus TCP / IP interface for Ouflex M BA device
GSM modem	By connecting the Ouman GSM modem to the Ouflex M BA, you can communicate with text messages to device and receive alarms to GSM phone.
Additional Control panel	The Ouman LCD external display is connected to the flap cover over the RJ12 jack. Use Ouman cable LCD CABLE M.

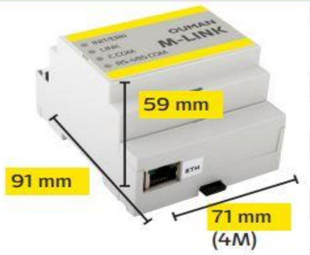
XM1362_Ouflex M BA_User manual_ENG_ 20180912

CE

Saving energy, creating comfort

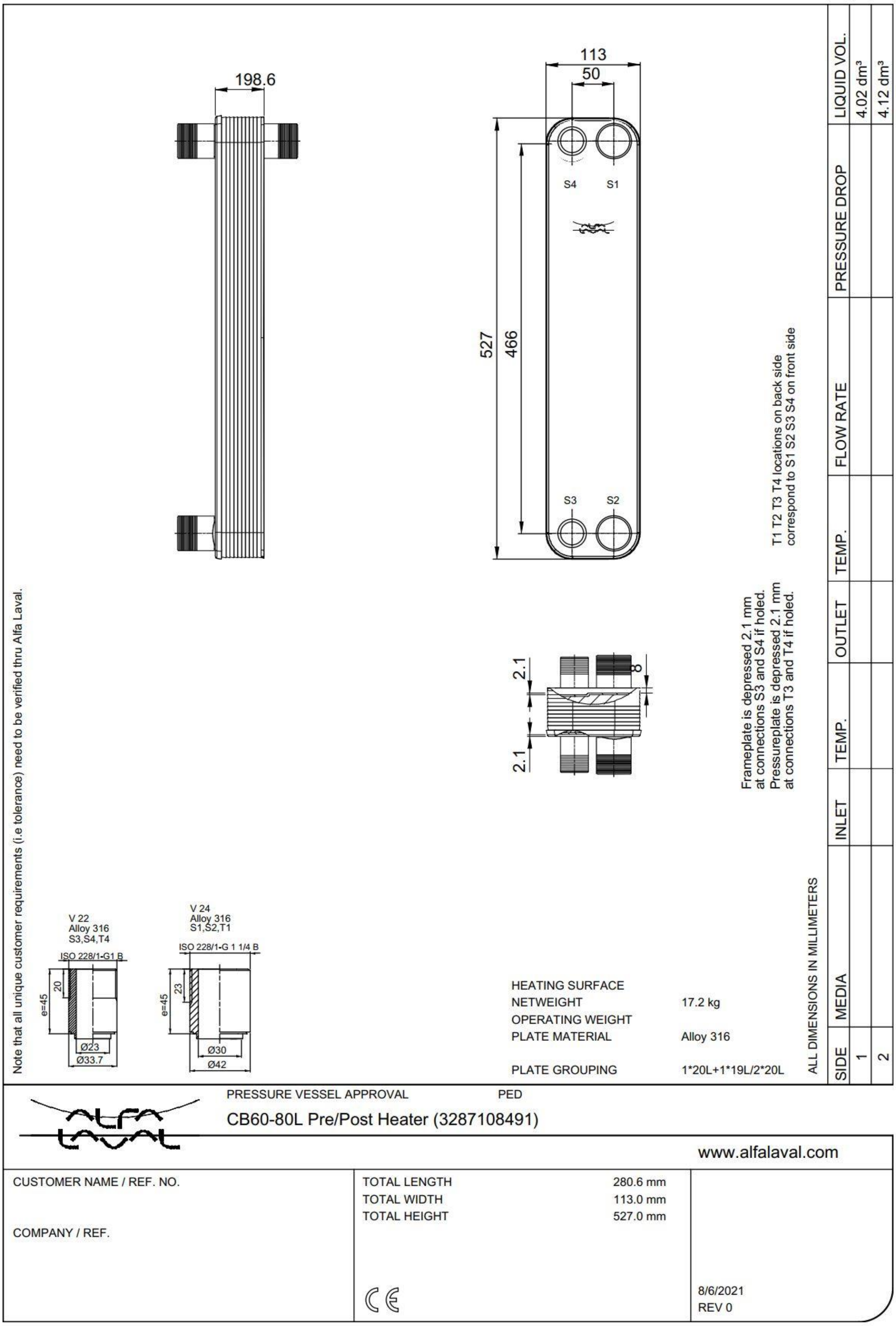
OUMAN

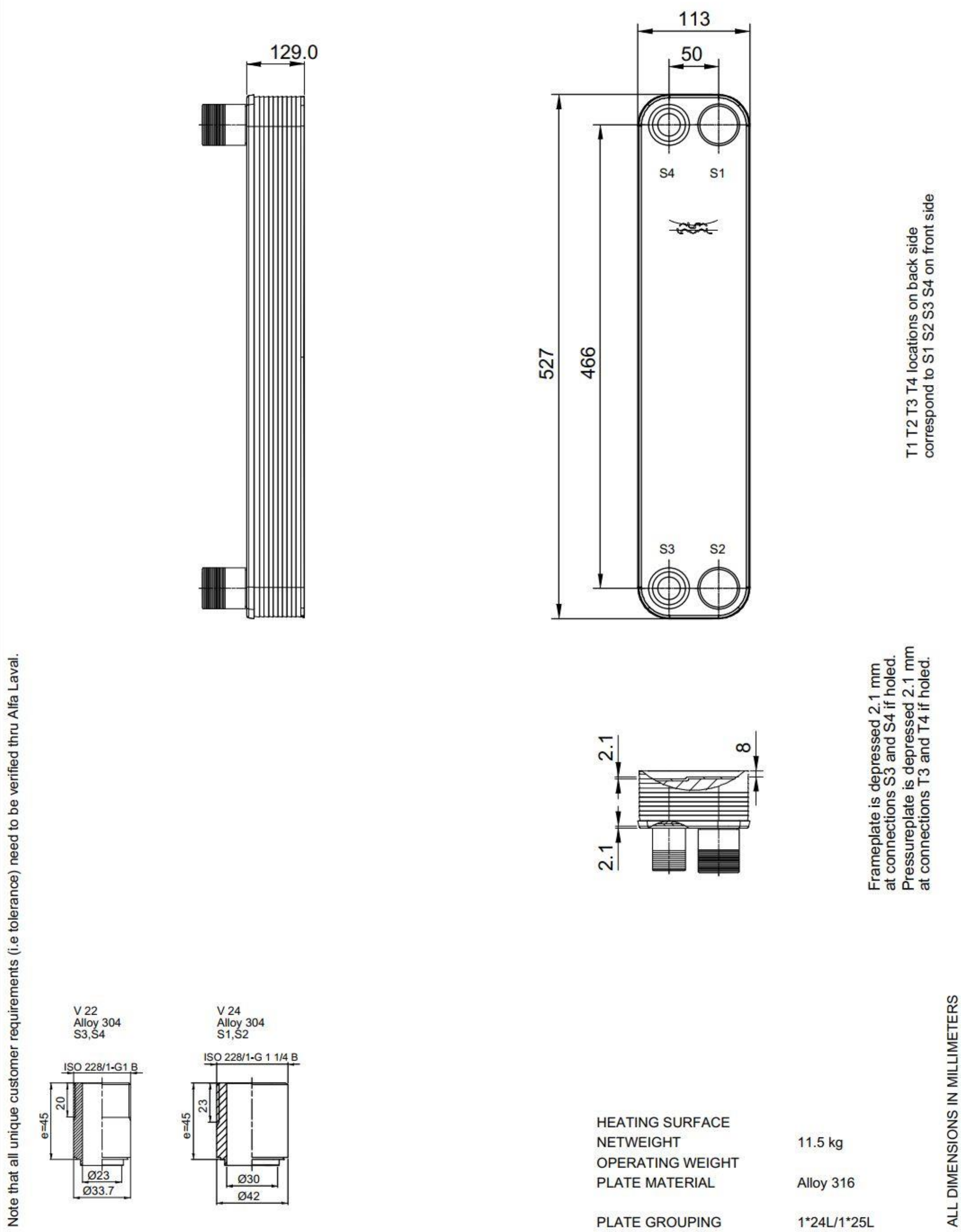
M-LINK	Technical information
Casing	PC/ABS
Mounting	DIN rail
Dimensions	71 mm (4M) x 91 mm x 59 mm
Weight	100 g
Operating temperature	0 ... +50 °C.
Storage temperature	-20 ... +70 °C.
Protection class	IP 20
Ethernet connection	10/100 Mb/s Ethernet-connection (RJ-45)
Serial connections	RS-232, RS-485 Modbus- RTU
Operating voltage	16-30 VDC /1.4 W or 24 VAC (-20% ... +25%) / 3.6 VA
Ethernet protocols	Modbus TCP, HTTP, SNMP and FTP
Approvals - EMC Interference tolerance - EMC Interference emissions	 EN 61000-6-1 EN 61000-6-3
System dependency	Can be connected to Ounet. Modbus TCP/IP support
Warranty	2 years
Manufacturer	Ouman Oy



We reserve the right to make changes to our products without a special notice.

Appendix nr 5 - HEX dimension drawings





SIDE	MEDIA	INLET TEMP.	OUTLET TEMP.	FLOW RATE	PRESSURE DROP	LIQUID VOL.
1						2.47 dm³
2						2.58 dm³

HEATING SURFACE	
NETWEIGHT	11.5 kg
OPERATING WEIGHT	
PLATE MATERIAL	Alloy 316
PLATE GROUPING	1*24L/1*25L

PRESSURE VESSEL APPROVAL PED

CB60-50L-F (3287103737)

www.alfalaval.com

CUSTOMER NAME / REF. NO.		
COMPANY / REF.	TOTAL LENGTH 174.0 mm TOTAL WIDTH 113.0 mm TOTAL HEIGHT 527.0 mm	8/24/2017 REV 0

CE

Appendix nr 6 – Comparison sites

In the comparison sites, the A stands for Astangu, e.g., if the comparison site would be named A1, then it would refer to Astangu street, building nr 1.

June - August							
Year	**Site**	**Demand, MWh/y**	**Flow volume, m3/y**	**dT', °C**	**Peak demand, MWh**	**T1, °C**	**T2, °C**
2019	A26	26	1268	17,4	0,03	63,2	45,7
	A32	19	1077	15,0	0,0253	64,5	49,5
	A34	26	1014	22,1	0,03	65,7	43,6
	A36	24	976	20,9	0,0243	64,5	43,6
	A38	28	1260	19,1	0,0301	67,5	48,4
	A42	27	904	25,6	0,03	70,5	44,9
	A44	20	439	39,2	0,0259	68,0	28,7
2021	A26	26	1149	18,6	0,03	64,3	45,6
	A32	18	929	16,1	0,022	65,7	49,6
	A34	26	977	22,7	0,03	67,1	44,4
	A36	21	703	25,7	0,02	63,8	38,1
	A38	24	1073	19,1	0,03	68,3	49,2
	A42	26	908	24,8	0,03	71,8	47,1
	A44	23	651	30,0	0,027	69,7	39,7

Appendix nr 8 – Dimensioning sheet of the new HSS for site A36

Cetetherm

Technical specification Maxi C1S

General information		Technical information	
Configuration number	2020.11.27/2200/5391	System category	Cetetherm Maxi C1S
Name	Template Tallinn Utilitas 2-Circuits (Copy)	System setup	Domestic hot water and heating, 2-step
Model	C1S-BALTIC		

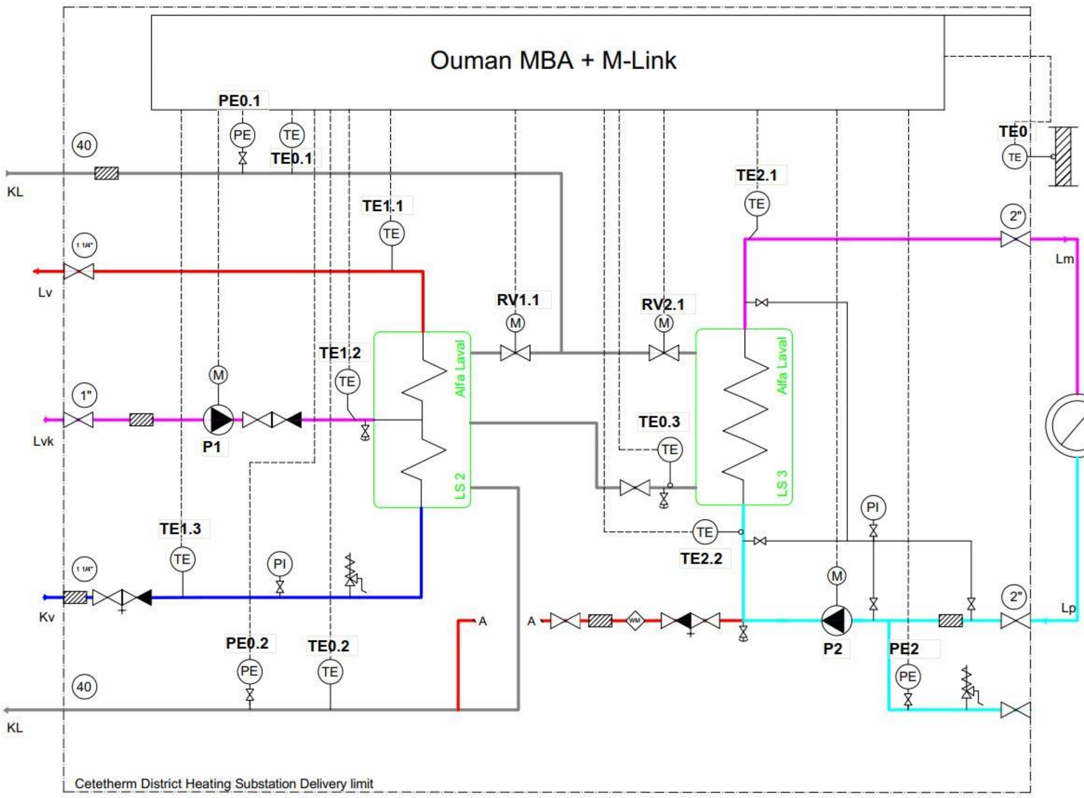
Comment

C203 will be swithced to Ouflex M BA without software.
Includes Ouman M-Link module for remote monitoring and control in Web UI including Web UI access.
Rex router 4G included for. SIM card and subscription not included.
Access to separate Ounet service not included and not needed. Can be added with existing module if needed in the future.
2 extra surface sensors included for monitoring of district heating flow and return temperatures.

Calculated available differential pressure of primary network: min 60 kPa / max 600 kPa

		Primary	DHW Section		Heating 1	
Design data						
Temperature	°C	120	90		100	
Pressure	bar	16	10		6	
Heat exchangers						
Capacity	kW		151		132	
Model / Type			CB60-80L :2		CB60-50L 6C-HES	
			Primary	Secondary	Primary	Secondary
Temperature	°C		60 / 21.4	8 / 55	100 / 52.5	50 / 70
Flow	l/s		0.94	0.77	0.66	1.58
Pressure drop	kPa		13	11	3	12
PED category			Cat 1		Art 4.3	
Control valves						
Manufacturer			Ouman		Ouman	
Control valve			VD2_		VD2_	
KVS			4		4	
CV flow	l/s		0.94		0.66	
Control valve pressure drop	kPa		72		35	
Actuator			M41A15		M31A150	
Control signal / voltage	V		0-10 V / 24V		0-10 V / 24V	
Summer shut off valve						
Connection type					2-step	
Controller						
Manufacturer		Ouman				
Control center		Ouman C203 (OK-2C combibox, export)				
Controller		C203				
Pumps						
Manufacturer			Grundfos		Grundfos	
Pump			Alpha 2 15-60-CIL2		Magna3 25-100	
Pump flow	l/s		0.27		1.58	
lifting height	kPa		31		42	
Max lifting height	kPa		47		62	
Network pressure drop	kPa		30		30	
Power / Current	W / A		45 / 0.38		153 / 1.33	
Voltage	V		230V 1~		230V 1~	
Secondary side components, DHW						
Pipe size / Connection type			DN32 / G 1 1/4"			

		Primary	DHW Section	Heating 1
Circulation pipe size / Connection type			DN25 / G 1"	
Circulation valve			Shut-off valve DN25, G 1"	
Safety valve			10 bar DN15	
Cold water strainer			Strainer G1 1/4"	
Circulation strainer			Strainer G1"	
Manometer in cold water pipe			Manometer	
Secondary side components, heating				
Pipe size / Connection type				DN50 / G 2"
Valve supply				Shut-off Valve DN50, G 2"
Filling				Filling from DH return + water meter
Safety valve				6 bar DN20
Manometer				Manometer 4-Point + Place for pressure sensor
Exp. section service shut off				Shut off valve. DN25, G1"
Pressure sensor				PX2.100P 0-6,8 bar, pressure sensor
Strainer				Default
Temperature sensors				
Flow pipe			TMW-100-C, immersion sensor, 100mm	TMW-210-C, immersion sensor, 210mm
Return pipe				TMS-C, surface sensor
Primary return				TMS-C, surface sensor
DHW circulation temperature sensor			TMW-210-C, immersion sensor, 210mm	
Thermometers				
Primary side equipment				
Primary main pipe size		W40		
DH Strainer		Lifin HVH Welded		
Pressure metering		QBE9200-P16 with shut off in Prim. flow & Ret.		



Appendix nr 9 – Base dimensioning sheet of the HEX calculations

SWEP International AB
Box 105, Hjalmar Brantings väg 5
SE-261 22 Landskrona, Sweden

www.swep.net

SINGLE PHASE - PERFORMANCE
HEAT EXCHANGER: B85Hx100/1P

SWEP SSP G8 2022.421.1.0

Date: 21/05/2022

SSP Alias: B85

DUTY REQUIREMENTS		**Side 1**		**Side 2**
Fluid		**Water**		**Water**
Flow type			**Counter-Current**	
Circuit		Inner		Outer
Heat load	kW		**132,0**	
Inlet temperature	°C	**75,00**		**50,00**
Outlet temperature	°C	53,05		**70,00**
Flow rate	kg/s	1,436		1,577
Thermal length		5,568		5,073

PLATE HEAT EXCHANGER		**Side 1**		**Side 2**
Total heat transfer area	m²		5,88	
Heat flux	kW/m²		22,4	
Mean temperature difference	K		3,94	
O.H.T.C. (available/required)	W/m²,°C		5700/5690	
Pressure drop - total*	kPa	10,5		12,1
- in ports	kPa	1,37		1,65
Port diameter (up/down)	mm	33,0/33,0		33,0/33,0
Number of channels per pass		49		50
Number of plates			100	
Oversurfacing	%		0	
Fouling factor	m²,°C/kW		0,000	
Reynolds number		1179		1196
Port velocity (up/down)	m/s	1,71/1,71		1,88/1,88
Channel velocity	m/s	0,160		0,172
Shear stress	Pa	16,0		18,4
Average wall temperature	°C	62,13		61,83
Largest wall temperature difference	K		0,41	
Min./Max. wall temperature	°C	51,62/72,66		51,37/72,25

**Excluding pressure drop in connections.*

PHYSICAL PROPERTIES		**Side 1**	**Side 2**
Reference temperature	°C	64,02	60,00
Dynamic viscosity	cP	0,440	0,467
Dynamic viscosity - wall	cP	0,452	0,454
Density	kg/m³	981,1	983,2
Heat capacity	kJ/kg,°C	4,188	4,185
Thermal conductivity	W/m,°C	0,6581	0,6544
Film coefficient	W/m²,°C	12200	12600

TOTALS		**Side 1**		**Side 2**
Total weight empty (no connections)*	kg		15,76	
Total weight filled (no connections)*	kg		24,9	
Hold-up volume (Inner Circuit)	dm³		4,61	
Hold-up volume (Outer Circuit)	dm³		4,7	
Port size F1/P1	mm		33	
Port size F2/P2	mm		33	
Port size F3/P3	mm		33	
Port size F4/P4	mm		33	
Carbon footprint	kg		110,74	

**Weight depends on the selected product.*

Appendix 10 – Chemical content of mains water

AS UTILITAS TALLINN

Tehnilise Toe Osakond

Keemialabor

Vee analüüside võrdlustabel.

Kuupäev: 10.11.2020.a

Näitaja	Ühik	AS Utilitas Tallinn'a keemialabor			HSY veelabor, Soome	
		Tallinna linnavesi (2020.a keskmine näit)	**Lääneterminaal**	**Vantaa**	**Pitkäkoski**	**Vanha-kaupunki**
pH		7,23	8,29	7,76	8,4	8,4
El.juhtivus	μS/cm	437,5	158,4	152,2	152	158
Karedus	0dH	10,25	2,94	2,69	2,9	3,1
Leelisus	mmol/l	2,6	0,75	0,65	0,73	0,77
Kloriidid	mg/l	33,16	6,0	6,0	4,8	4,80
Raud	mg/l	0,33	0,012	0,05	0,026	<0,02
Kaltsium	mg/l	58,8	19,4	17,2	19,0	19,0
Magneesium	mg/l	8,4	0,96	1,2	1,6	1,6
Vask	μg/l	6,08	0,4	0,8	0,3	0,7

N.Kabrda

Keemialabori juhataja

Appendix 11 – Design of test site's old HSS