DOMESTIC HOT WATER CONSUMPTION AND ITS IMPACT ON SYSTEMS WITH CIRCULATION

Master's Thesis (M.Sc.)

Group members: Plamen Burnazov
Dimitar Apostolov
Supervisor: Rasmus Lund Jensen
Olena Kalyanova Larsen
Building Energy Design
Department of Civil Engineering
Aalborg University

AALBORG UNIVERSITY
STUDENT REPORT

Building Energy Design
Department of Civil Engineering
Thomas Mann's Vej 23
DK 9200 Aalborg SV
Denmark
Phone: +45 9940 8484
E-mail: civil@civil.aau.dk

TITLE:

Domestic hot water consumption and its impact on systems with circulation

THEME:

Analyzing variations in use of domestic hot water in a student accommodation building and investigations on the resulting performance of hot water systems with circulation

PROJECT PERIOD:

Autumn semester, 2016

PARTICIPANTS:

Plamen Tsvetanov Burnazov

Dimitar Apostolov

SUPERVISOR:

Rasmus Lund Jensen

Olena Kalyanova Larsen

NUMBER OF PAGES: 76

APPENDIX PAGES: 22

COMPLETED ON: 13.01.17

SYNOPSIS

The following report analyzes the consumption of domestic hot water in a dormitory building located in Aarhus. Available literature and research are reviewed on the topic. The data analysis section of the report presents the available data for hot water usage provided by the housing association and investigates the variation of consumption with regards to monthly and seasonal variation, as well as weekdays and weekends. Additionally, by building several system simulation models, using input parameters from the data analysis and information about the building, investigate possible system inefficiencies. Alternative systems are compared with regards to their performance. A conclusion is being drawn on the results from the simulations with some concepts and suggestions for further improvement of the systems.

ABSTRACT

This report aims to investigate the variation of domestic hot water use in residential buildings and develop general yearly profiles. Furthermore, discuss the performance of domestic hot water systems with circulation loop, compare to some alternative systems and draw conclusions and suggestions for the better utilization of the systems based on that.

Domestic hot water usage results in a significant part of a building's total energy consumption. A more detailed understanding of how and when occupants use domestic hot water could be of high importance for design and sizing of energy systems, as well as estimating their energy use in the early design phase. Several studies and research have been performed in different countries regarding the consumption of DHW in terms of monthly, seasonal, weekday-to-weekend and hourly variations.

This report investigates the daily data for DHW use in a dormitory building consisting of 99 apartments situated in Aarhus, Denmark. Variations of consumption are presented as a function of time and a comparison is done for the four available years, with monthly, seasonal and weekday-to-weekend variation.

The analysis shows that the average daily consumption on a year to year basis remains similar for the measured period of four years. The consumption in the summer period is relatively lower compared to the winter period as there is a high frequency of instances with no consumption during the month of July, possibly due to the absence of occupants in the holiday season. In contrast, the peak consumption occurs during the month of February. In the summer period, smaller volumes of hot water per day tend to be used more often compared to the winter period.

Investigating the weekday-to-weekend variations suggests that the overall consumption rate for weekdays was up to 8% higher than on weekends. Excluding the days with no consumption shows that the weekdays and weekends have minor difference in the actual total daily consumption.

The information from the data analysis is used for a simulation model setup that resembles the actual DHW system installed in the dormitory building in Aarhus. This benchmark system is used for comparison with other solutions for DHW systems in order to address their inefficiencies and the total energy consumption. The issues of hot water circulation temperatures, return DH temperatures and temperature sensor placement are among the varied parameters that have an influence on the total energy use of the system.

The placement of the temperature sensor for activating the circulation loop has an impact on water temperature delivered at the tap. Placement of the temperature sensor on the circulation loop can

cause water circulation during tapping which can decrease the efficiency of the system and increase the temperature of the return water on the primary side of the system.

The frequency and the volume of tapings has an influence on the circulation and on water temperature at the tap. The investigated parameters are not quantified for the most part, as for the software used for the analysis is not suited for that purpose. Further research can be conducted using more advanced software for that purpose. Alternative domestic hot water systems with an el-tracing and a storage tank can for some application show better performance than systems with circulation. However, it is concluded that the design is very much case dependent.

CONTENTS

1 INTRODUCTION

In this report it is investigated how domestic hot water is used in a student accommodation multistorey apartment block building. The available data from a real building is analyzed and observations are presented based on the hot water usage from the measured period. Furthermore, some common systems for domestic hot water are discussed. In addition analysis of a typical system is performed and comparison with other commonly used systems is made.

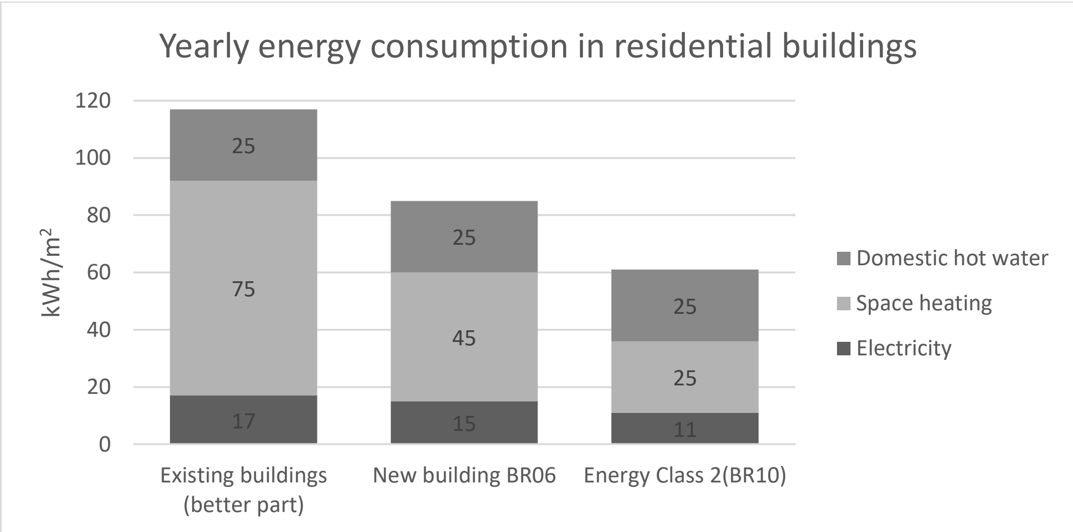
The increasing requirements on lowering the energy use of buildings is headed towards setting a zero energy demand in the not so distant future. However, domestic hot water use has not been on the forefront of reducing energy use in buildings, despite of the potential of contributing for the reduction of energy use. Therefore, it is important to investigate variations in domestic hot water use over time and for different number of occupants or as a function of other factors to gain a better understanding of how DHW use influences energy performance. Furthermore, investigating inefficiencies in the supply system for domestic hot water in buildings, both as a result of variation in use and as inherited inefficiencies by design is also of importance. Investigations in those areas could potentially lead to a better understanding of the connection between the use, production and supply of domestic hot water and thus help design more efficient systems.

Firstly, data for domestic hot water consumption provided by the housing association administrating the case building is gathered and analyzed, and conclusions are drawn based on the variation of usage. Several user profiles are presented, based on both research of available literature and actual measured data. Secondly, domestic hot water production and distribution by means of systems with active circulation look in apartment block buildings is discussed and suggestions for improvement of delivery methods and alternative systems are made.

2 DOMESTIC HOT WATER

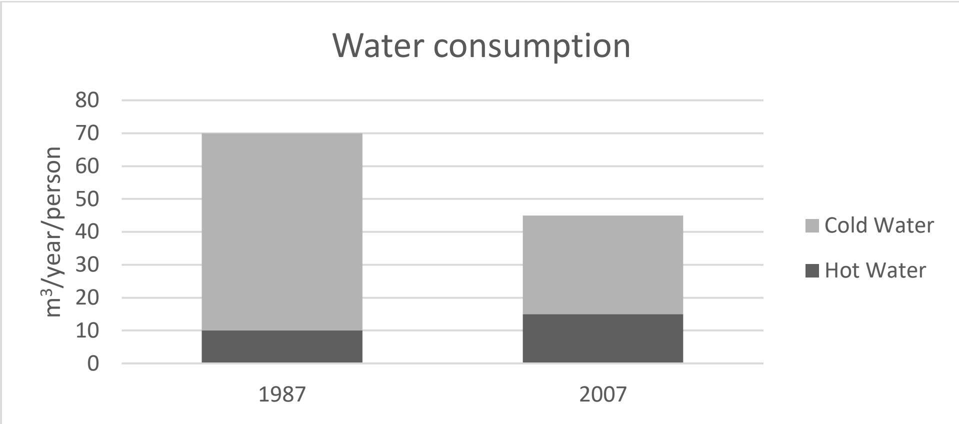
2.1 BACKGROUND

The tightening of the energy requirements for buildings in recent years has mainly had an impact on the reduction of energy use for space heating and electricity, while the expected energy use for domestic hot water has remained relatively unaffected over many years. That could be a consequence of the way domestic hot water systems are designed and operated, as well as the constant need and relatively unchanged in terms of volume domestic hot water from the occupants. As a result of the improved building envelope, the energy use for domestic hot water becomes a more significant part of the overall energy frame of a building. This is illustrated in Graph 2.1 based on a research done by the Danish Building institute (1).



GRAPH 2.1 DISTRIBUTION OF ENERGY USE FOR DOMESTIC HOT WATER, SPACE HEATING, ELECTRICITY ACCORDING TO DIFFERENT ENERGY CLASS BUILDINGS (1)

Available research has presented some investigation in the area of water for domestic use in buildings and how the occupants use it. According to Energistatistik 2014 (2) the overall use of water has fallen over the recent years. However, looking at the available literature it can be concluded that even though as a whole the water consumption in Denmark has been reduced, the consumption of domestic hot water has risen. That is concluded in a report published by Danish Building Institute (1). In this report the authors present a comparison, seen in Graph 2.2, of the water consumption for 1987 and 2007 where this tendency is illustrated.



GRAPH 2.2 DEVELOPMENT OF HOT AND COLD WATER USE (1)

This increased use of hot water in the recent years only add to the importance of further investigating the use of DHW and energy for DHW.

2.2 PROBLEM

Hot water is produced in buildings using one of various energy sources or a combination of several. In Denmark, especially in urban areas, energy for domestic hot water is often provided by district heating through a heat exchanger or a storage tank with an internal heat exchange in the building. Another source for heating of DHW is a boiler, which can be powered by various types of fuel or electricity. Nowadays more often renewable energy sources are used in building applications, such as solar thermal panels for DHW. A network of pipes and fittings are then used to distribute the water to the taps in the building. Inherently for DHW system there are heat losses to the surroundings. After each tapping there is a remaining volume of water standing in the system with temperatures around and sometimes more than 50°C. The water in the network of pipes is then maintained at a minimum temperature of around 40°C in order to avoid a long waiting time for hot water to reach the far end of the system at next tapping.

In energy calculations the heat energy lost by the system in what is considered the heated part of a building is assumed to be utilized as free heat energy, which therefore is considered to reduce the heating need in the building. However, in their general conclusion, the Danish Building Research Institute argue that only about 10% of the heat loss from DHW systems in residential buildings is utilized and only about half of the total energy is delivered.

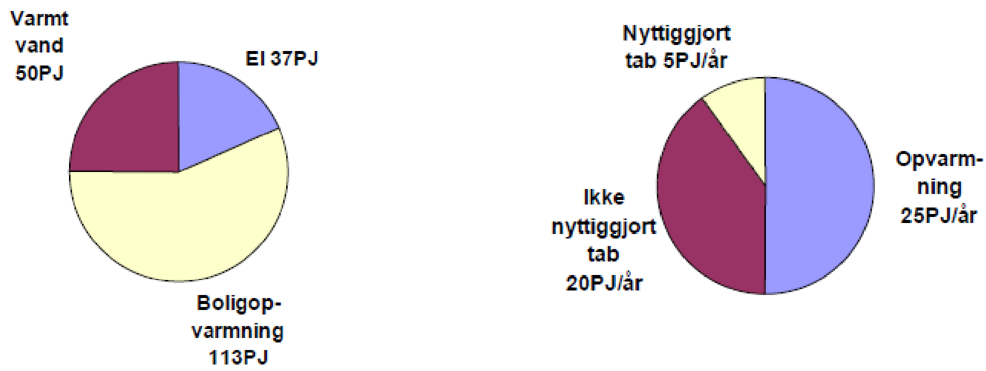


FIGURE 2.1. DISTRIBUTION OF ENERGY IN A HOUSEHOLD AND IN A DOMESTIC HOT WATER SYSTEM[1]

During periods where there is no tapping of hot water, energy is constantly spent on maintaining high temperature in the pipe network and recirculating the water, for systems with circulation loops. The magnitude of that issue is particularly high in multistorey residential buildings and office buildings, where the piping network is relatively long and tapping is inconsistent. The Danish Building Institute estimate in their report that in multistorey apartment block buildings and office buildings the losses from circulation can be up to respectively 60% and 70% as opposed to 36% for single family houses(1).

Relating the energy use to the user behavior is a relevant point when discussing any type of energy systems in buildings. In this case the way people use hot water can have direct influence on the amount of energy losses or energy that is not utilized by the users. The lack of knowledge on how occupants use water and where inefficiencies in the systems lie hampers the unveiling of the potential for energy savings in that area.

2.3 GOAL

This report deals with analysis of the domestic hot water consumption in an apartment block building with regards to yearly and monthly variation in consumption and periods without consumption. Furthermore, a research on DHW use during the day is done, where hourly profiles are drawn and periods with no water use are discussed. The goal is to find and present factors and dependencies that influence the DHW use. The concluded information is then related to the issue of different losses in a DHW system. The purpose is to conduct a detailed investigation of the causes of the issue and present possible solutions.

[1] The total energy consumption for a household concluded by Energistatistik in a report from 2007 is 200 PJ/year (2)

3 LITERATURE REVIEW

This chapter summarizes findings from published studies on the topic of domestic hot water (DHW) use in buildings. As part of the preparation for the analysis of domestic hot water use in an existing residential building the available literature on the topic is reviewed in order to gain a realistic perspective on what the use of water in similar cases could be and be able to compare it. [2]

3.1 OVERVIEW

The scope of this report includes only analysis of domestic hot water use in residential buildings as in this type of building relatively large amounts of water are consumed and therefore it is important to understand how the water is being used.

Typically, residential building are equipped with only one meter per residential unit, which usually is a flow meter and in some cases, a temperature meter for when energy use is measured. Also, often the measuring devices are not connected to a central logging system or if they are, only single daily readings are logged. That limits the possibilities for a detailed analysis of how water is used over time. However, a few studies have dedicated their effort on taking detailed measurements and analyzing them thoroughly. The results from those studies are presented in this section. Besides the volume of the used water, another interesting aspect of the use is the temperature at which water is used. By design, the water is delivered to the system with higher temperatures than the one that is actually used. Different consumer taps in a household rarely deliver water at very high temperatures. For example, when taking a shower the water temperature ranges between 40-42 °C, while the water in the system may circulate with temperatures of around and above 55 °C for most designs with DHW storage tank[3].

However, not many studies are conducted where these issues of higher than required temperatures and their impact on the systems and the users are addressed. More comprehensive knowledge on the topic can provide a benefit for both the energy system designers and the users.

DHW use can vary significantly across a wide range of applications. This variation is a result of objective and to an extent quantifiable factors such as number of occupants, as well as subjective factors such as climate, cultural behavior, age, income, etc. Unfortunately, the subjective factors often outweigh the objectives, thus resulting in an significant variation of results and conclusions when comparing

[2] References in this chapter are specifically listed under Bibliography at the end of this report.
[3] Temperatures of above 55°C are often required in storage tanks in order to prevent the development of legionella bacteria in the water (13).

similar household setups in similar conditions. Therefore, in the available literature the authors often derive models for the DHW use with great variations.

Table 3.1 shows a summary of results of studies conducted. It is notable that even though the research and measurements are performed in similar conditions, the results are not entirely affected by quantifiable factors, but can also be influenced by geographical and sociological factors.

Research	Year	DHW use		Comment
		Liters Daly per Household (AVG)	Liters daily per capita	
Pearlman, Mills	2003	236 l/d	47-86 l/d	Research conducted in Ontario, Canada and used to form the basis for ASHRAE HVAC Application Handbook
Becker, Stogsdill	1990	239 l/d	-	Research based on several DHW studies prior to 1990
Swan	2011	208 l/d	67 l/d	Canadian research, based on 16 952 houses
DeOreo, Mayer	2000	262 l/d	-	Research based on 1188 homes in 12 different sites

TABLE 3.1 SUMMARY OF THE DHW USE ACCORDING TO VARIOUS STUDIES

3.1.1 DOMESTIC HOT WATER PROFILES AND THE IMPACT OF DHW USE ON ENERGY USE

The building sector consumes between 16 – 50% of the total energy in most countries across Europe, with domestic hot water contributing for a relatively large percentage of the total energy use. [1] DHW in residential buildings is used for different purposes of higher and lower consumption – showering, bathing, laundry, cleaning and washing, etc. As previously mentioned, the differences in consumption rates are depended on several factors related to residential occupancy such as number of residents, occupant behavior, appliances, life style, demographic conditions, etc. Thus, an attempt to create individual consumption profiles for different occupants can be a rather difficult task; there are far too many uncertainties involved when it comes to occupant behavior and individual comfort, making the DHW consumption vary significantly from one occupant to another.

Previously, several studies have focused on the relation between occupancy and domestic hot water consumption. One study [2] has derived a linear relationship between the two, where 45 l/day/per was the value added for each additional occupant in cases where the occupancy was above two persons per unit. Here the variation for the model is shown to be 21 l/day/per, which again confirms the high uncertainty.

Further investigations in other studies confirmed that the number of occupants is one of the key determinant of DHW use. Such studies have come up with similar linear relationships between the number of occupants and the DHW use. In addition, several studies have found that the DHW consumption is heavily influenced by factors such as ownership of the building, purpose and activity levels, age and income of the occupants, etc., but the combination of all those factors show inconclusive results.

Looking to studies conducted in conditions close to the Danish, consumption rates of residential apartment buildings in different Nordic and Baltic countries can vary significantly, despite the geographical similarities, according to a study conducted by Petri Pylsya and Jarek Kurnitski. The highest consumption rate was determined in Finland at 46 l/person/day [3], while the lowest was in Denmark at 40 l/person/day [4]. Hourly consumption rates are also different for different countries and largely related to the local customs and traditions. Climate, weather conditions and seasonal variation are another factor that influences the DHW consumption, primarily the volume and the energy required for heating the supply water in different periods of the year.

A study based in Finland [5] was focused on a monthly DHW user profile for a residential apartment building consisting of 182 apartments and 379 occupants, with regards to both monthly and weekly variations for the course of a year. The measured data has been used to calculate a mean consumption rate for DHW with a separate factor for each month, which is used to obtain monthly consumption rates in l per person per day. In addition, hot-to-cold water ratio was also investigated for these profiles. This was done for the purpose of providing more accurate input for designing solar thermal systems for domestic hot water.

The study has found that the annual DHW consumption mean value was 43 L/person/day, which is 3L less than the value used in the local building code. The common consumption rates were between 20-70 L/person/day. The average hot-to-cold water ratio was 0.39, which specific monthly variations between 0.35 and 0.41. The months of July and November showed significant variations of 38L/person/day and 48L/person/day, which required the use for monthly correction factors. The obtained profiles effect on the energy use was tested with dynamic simulation of solar thermal system. The derived monthly profile increased delivered energy by 4.7% compared to simulation without monthly variations. The weekday and weekend consumption variations did not have significant effect on delivered energy.

3.1.2 HOURLY CONSUMPTION PROFILES OF DHW FOR DIFFERENT OCCUPANT GROUPS

As mentioned in earlier studies, domestic hot water consumption profiles are difficult to define because of the large amount of variables, such as geographical, economic and social conditions, occupant behavior and number, weather conditions in different periods during the year, etc [6]. Some studies have identified some of the key factors as being the demographics of the location, occupant number, attitude toward usages, ownership and seasonal variations. A reference study [7] lists education, cultural and social norms as some of the more impactful factors, as it has measured the domestic hot water consumption in four apartment buildings in San Francisco for a period of 6 months and as well as conducted several interviews with the occupants in regards to DHW usage. [8] [9] [6] There have been several studies that have found a variation of DHW usages from day-to-day and seasonal variation, while others have addressed the occupancy number and patterns as having an impact on the domestic hot water demand. [10] [11]

Accurate hourly consumption profiles have been deemed necessary in several studies in order to perform evaluation for solar energy systems. [12] [13] The use of solar energy depends on availability of the solar radiation, the efficiency of solar energy system, and storage and user profile of energy consumption. In Nordic countries the solar resource is available in very short duration in a day during mid-autumn to mid spring. For Denmark, the availability of solar energy is 1160 kWh/m2/year and most of the radiation is generated in the period from May to August. There are a few studies focused on designing solar domestic hot water utilized a simplified daily profile (repeated hourly use for all months [14] [15] [16]. However, many researchers insist that more comprehensive hourly profiles are of great importance when it comes to developing and commissioning solar energy systems because factors like water consumption volume and usage patterns vary significantly in the weekdays and weekends, along the different months and seasons.

In a study about the consumer's influence on the domestic hot water systems, two separate load profiles were used in order to compare the systems' utilization of solar energy [17]. The researchers discovered that the more generic profile lead to a higher usage when compared to a more accurate and realistic user profile, which in terms resulted in a wrong sizing of the system and its components.

Consumer's influence was also the target of other studies which tested different storage tank and draw-off efficiencies, etc. They also concluded that the more realistic DHW profiles are required when testing and simulating storage systems. [18] [13] In a study conducted in Spain, a DHW storage system was designed and tested using dynamic user profiles based on 202 Spanish occupants in a large residential building. The reasoning behind this decision was that using generic user profiles based on average consumption patterns could lead to a "dampening" of the actual occupant usage behavior, and thus producing unrealistic results from the system, in terms of estimating the correct solar thermal storage. [23] A reference study to the one made in Spain was made on the efficiency and timing of the draw-off in a solar thermal system in relation to the specific user behavior, and yet again showcased the significance of realistic consumption profiles when dimensioning solar energy systems. [24]

Based on the majority of research sources reviewed, it can be concluded that utilizing more specific and accurate DHW profiles are important in the process of designing and sizing a wide variety of energy systems, such as DHW storage systems, solar thermal systems, geothermal heat pumps, etc. [19] [20] [21] [22].

A study focused on the hourly consumption for domestic hot water in different occupant groups in residential buildings in Finland [25] has created a method to estimate the hourly consumption with monthly correction factors for different occupancies ranging from a single person up to a large group of people without requiring extensive information about the individual preferences, DHW consumption and appliances. It was performed in a residential building with 86 apartments and 191 occupants in total, for the period of a year. The research has focused on hourly consumption patterns considering seasonal variations in spring, summer and winter time, generating profiles for 1, 3, 10, 31 and over 50 people for weekdays and weekends. They have validated their previous study by concluding that the daily average consumption of DHW in August, November and January were nearly similar to their previous study. During weekdays, the two peak consumptions were identified in the times between 7-9 AM and 8-10 PM, with an average consumption of 4.1 and 1.1 l/per hour for peak and non-peak hours respectively.

The research has created domestic hot water consumption hourly profiles for 5 different occupant groups as a function of the occupants' numbers, which can be used for a more precise estimation of the DHW usage regardless of the number of people occupying the building of interest. The conclusion which was drawn from the researched showed that the building size in relation to the size of the occupant group is of significant importance when creating a more specific DHW user profile. In terms of influence over the choice of tank for the hot water storage system, the generated profiles used in the research showed that the size of the tank needed to keep the same peak power demand could go up to 8.8 higher depending on the used profile compared to the benchmark standard model used for comparison. The top-up heating power was also largely dependent on the specific profiles, and showed a variation of up to 5.2 times higher requirement for top up heating. [25]

In addition, the research found out that the evening peaks were generally higher than the morning peak loads, and the average DHW consumption during peak hours was up to 4 times higher when compared to non-peak hours. The results from the conduced study provides relevant hourly consumption values that are intended to be used for sizing of system components and energy simulation software.

4 DATA ANALYSIS

Data for total daily consumption from an existing apartment block building is collected for a period of almost 4 years. The data is used to perform an analysis on the DHW use and relate it to the findings from similar studies. The low resolution of the data does not allow for analyzing the variation in hourly use and consequently deriving hourly profiles based on the measurements. However, the data is used to perform broader analysis of the DHW consumption, which could be relevant for various applications. In some instances, bulk amounts of data are missing, which is taken into account in the analysis. This issue limits the investigation to a certain extent, as it does not allow for entirely accurate yearly and monthly results. Table 4.1 shows the fraction of data that is missing for the different months and years. Illustration of the missing data is in 81Appendix A .

	2013	2014	2015	2016
Jan	55%	0%	0%	0%
Feb	37%	1%	0%	1%
Mar	1%	0%	0%	0%
Apr	82%	0%	0%	12%
May	1%	0%	0%	0%
Jun	0%	1%	1%	0%
Jul	29%	0%	0%	0%
Aug	13%	0%	0%	9%
Sep	0%	0%	10%	13%
Oct	0%	0%	10%	13%
Nov	1%	0%	1%	
Dec	0%	0%	0%	
Year	18%	0%	2%	

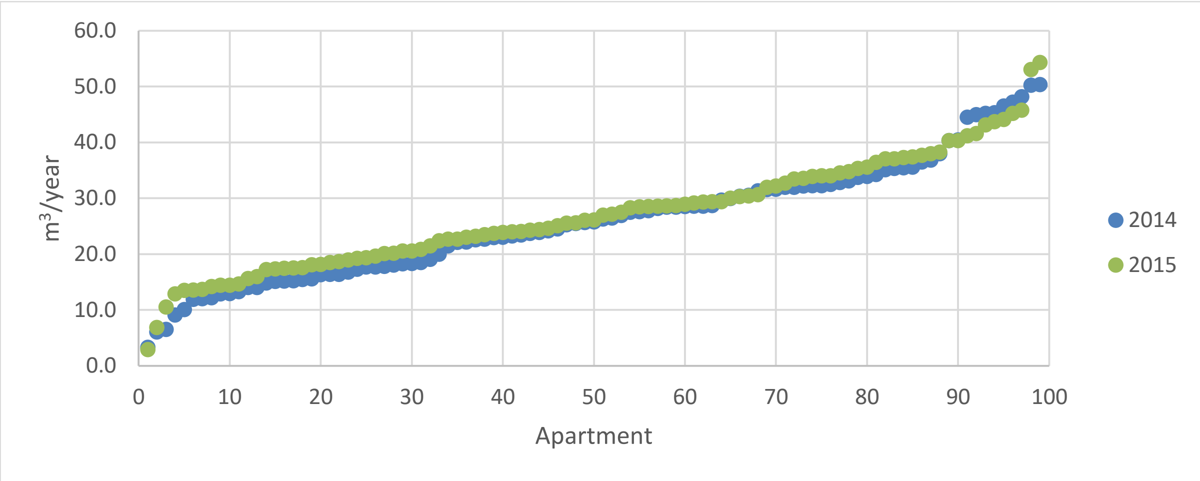
TABLE 4.1 AVAILABLE DATA FOR MONTHS AND YEARS

However, since the number of apartments and the duration of measurements are relatively big, excluding some of the data should not have a big influence on the overall results.

4.1 AVERAGE CONSUMPTION AND VARIATIONS AT APARTMENT LEVEL

The consumption of hot water can be of significant variation not only on a large scale but also from household to household in the same building. As shown earlier, in the available literature, models for DHW use are often derived as a function of the number of occupants. In these studies, measurements on households have been carried out, where the number of people per household was known and such representation of the models was possible. This way of presenting variations can be useful, as the number of occupants is easily predicted and quantifiable. In this case study, however, each apartment is occupied by either 1, 2 and in rear occasions 3 people, but the information about the actual number of people in the respective apartments for the time of the measurements is not available. During a site visit, the number of registered people per apartment was noted down and additional information with that regard was provided to the project group by the janitor of the building. At the time of the visit (28 November 2016) the total number of registered people was 184, of which 14 lived in an apartment of their own. The rest of the apartments were occupied by two or, as informed by the janitor, a couple of young families with a child.

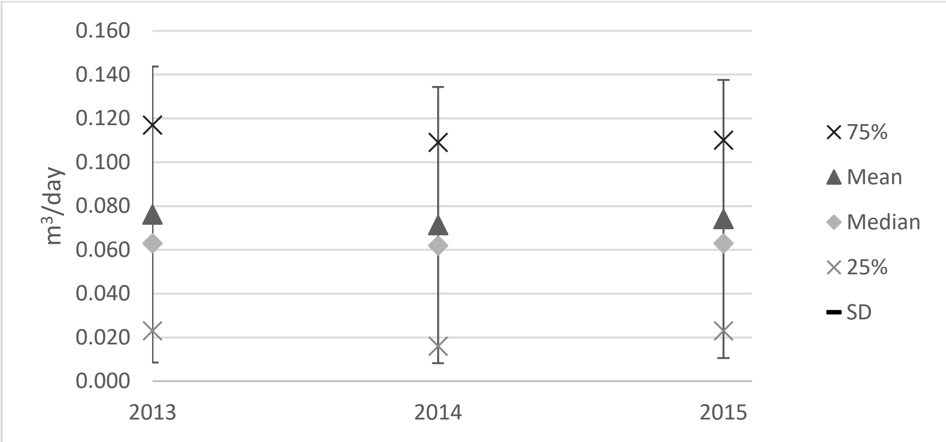
Attempting to investigate the number of people per apartment by comparing their total yearly water consumption did not lead to conclusive results. According to the derived models in the reviewed literature, for every additional person in the household the consumption, being either average daily or total yearly, increases with distinct value. However, the variation of those values is often large and simply looking the data can be misleading when assumptions regarding the number of people are made.



GRAPH 4.1 YEARLY DHW CONSUMPTION PER APARTMENT SORTED IN ASCENDING ORDER

As seen on Graph 4.1, there are no distinct jumps in the total yearly consumption for the apartments, when sorted in an ascending order from the smallest to the largest total yearly consumption. That is an indicator for the width of the spread in consumption per person, as one person household can use as much or even more than a two people household average consumption. Based on this observation, it can be concluded that the measured spread of water consumption can apply for one and two people households. The plot is also in agreement with the conclusion often found in reviewed literature sources, that a linear dependency cannot be applied to smaller households due to the large variation.

Taking a different approach when analyzing the data is to include the spread of the DHW use. However, often the whole spread is not indicative of the use, if only the magnitude is the focus. Therefore, the spread is represented using a statistical method of depicting the spread by quintiles, excluding the absolutes, as they occur rarely and therefore can be irrelevant when comparing data sets. The quintiles are useful when illustrating the frequency of occurrence of a value in a dataset and also indicate the probability of the event happening repeatedly.

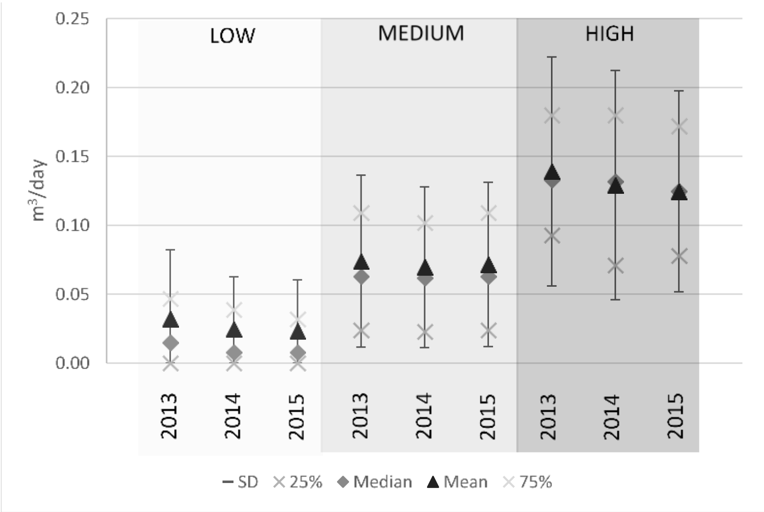


GRAPH 4.2 AVERAGE DAILY WATER CONSUMPTION AT APARTMENT LEVEL

Graph 4.2 summarizes the consumption for three consecutive years by presenting the median, mean and the spread of the data by using 25% and 75% quintiles. The three years show very similar consumption both in terms of mean daily consumption per apartment, but also in terms of the spread of the consumption. This indicates that the overall usage pattern and composition of the occupant group has remained similar throughout the years. That can be expected, as the building is a student accommodation block.

Since the number of people in each apartment for the period of measurements is unknown and could not be derived from the data, the consumption is divided into three groups: low, medium and high. The likelihood of the consumption for one person household to fall in low is greater than for it to rise high and vice versa with the consumption of two people household. For the division, the 25% percentiles and the 75% percentile for the daily consumption of the whole data set for each year are used. The lower quarter of the use is taken as low, the middle half as medium and the upper quarter as high. The values at the 25% and 75% quintiles are then used as a reference to compare the median values of the use for each apartment, to determine which category of use it falls into.

On average 9% of the apartments fall into Low consumption group, 82% fall into Medium consumption group, and 8% into High consumption. The average daily DHW consumption based on data for 2013, 2014 and 2015 is 33.0 l/d, 70.8 l/d and 126.0 l/d respectively for low, medium and high use.



GRAPH 4.3 DISTRIBUTION OF HOT WATER CONSUMPTION BETWEEN THE DIFFERENT USER GROUPS

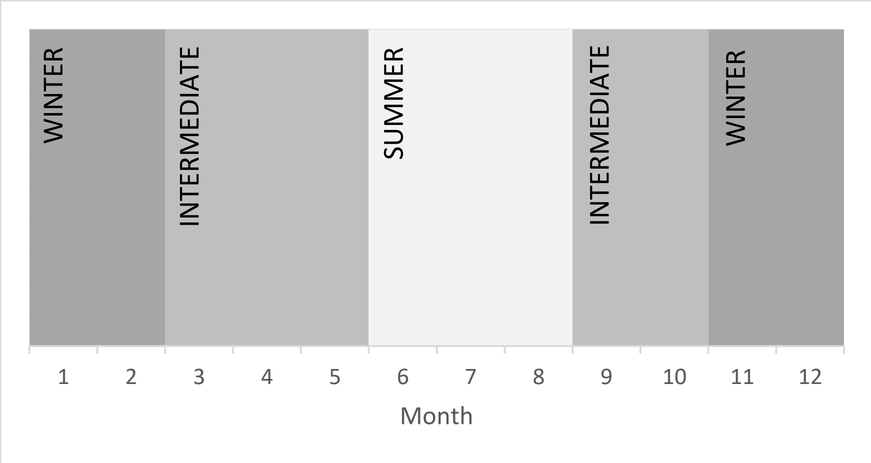
Expectedly, the biggest number of apartments falls into the category of medium use.

4.1.1 SEASONAL AND MONTHLY VARIATION

Estimating the yearly averages can be useful to track the progression of the water consumption. However, on a minor scale, information about seasonal or monthly consumption can be useful when designing DHW systems or to improve existing systems and their control strategy, as suggested in the literature. That could be particularly important in buildings equipped with renewable energy systems when estimating energy yield and the return of investment, as well as at a later stage when analyzing and commissioning their performance.

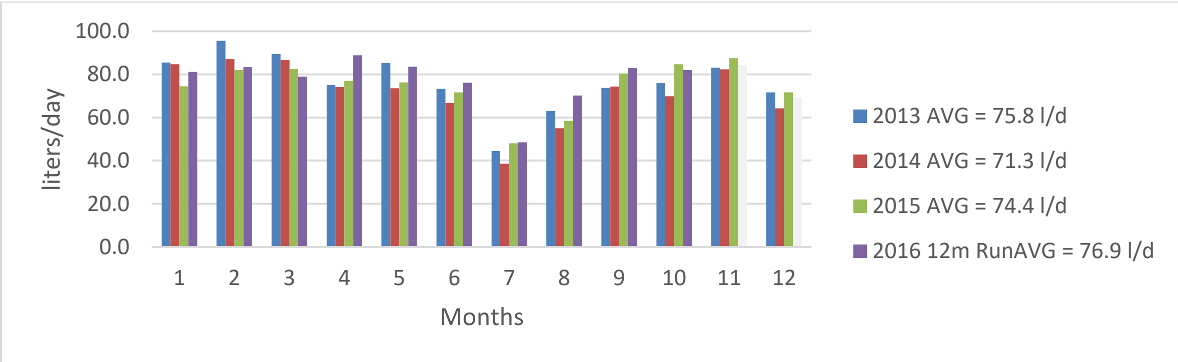
The focus of this part of the report is to gain knowledge of DHW use for the specified user group, as indicated by the seasonal and monthly variation of use. Since the case building is situated in Denmark, there could be a lack of clear distinction between the calendar seasons of the year. Typically, when talking about building energy performance in Denmark, the year is divided into a heating and non-heating season.

However, there is not a clear connection between DHW use and space heating energy use, therefore the year for the purpose of the analysis is divided into three: Winter (01.11-28.02), Summer (01.06-31.08)and Intermediate period (01.03-31.05; 01.09-31.10). This division is illustrated on Graph 4.4:



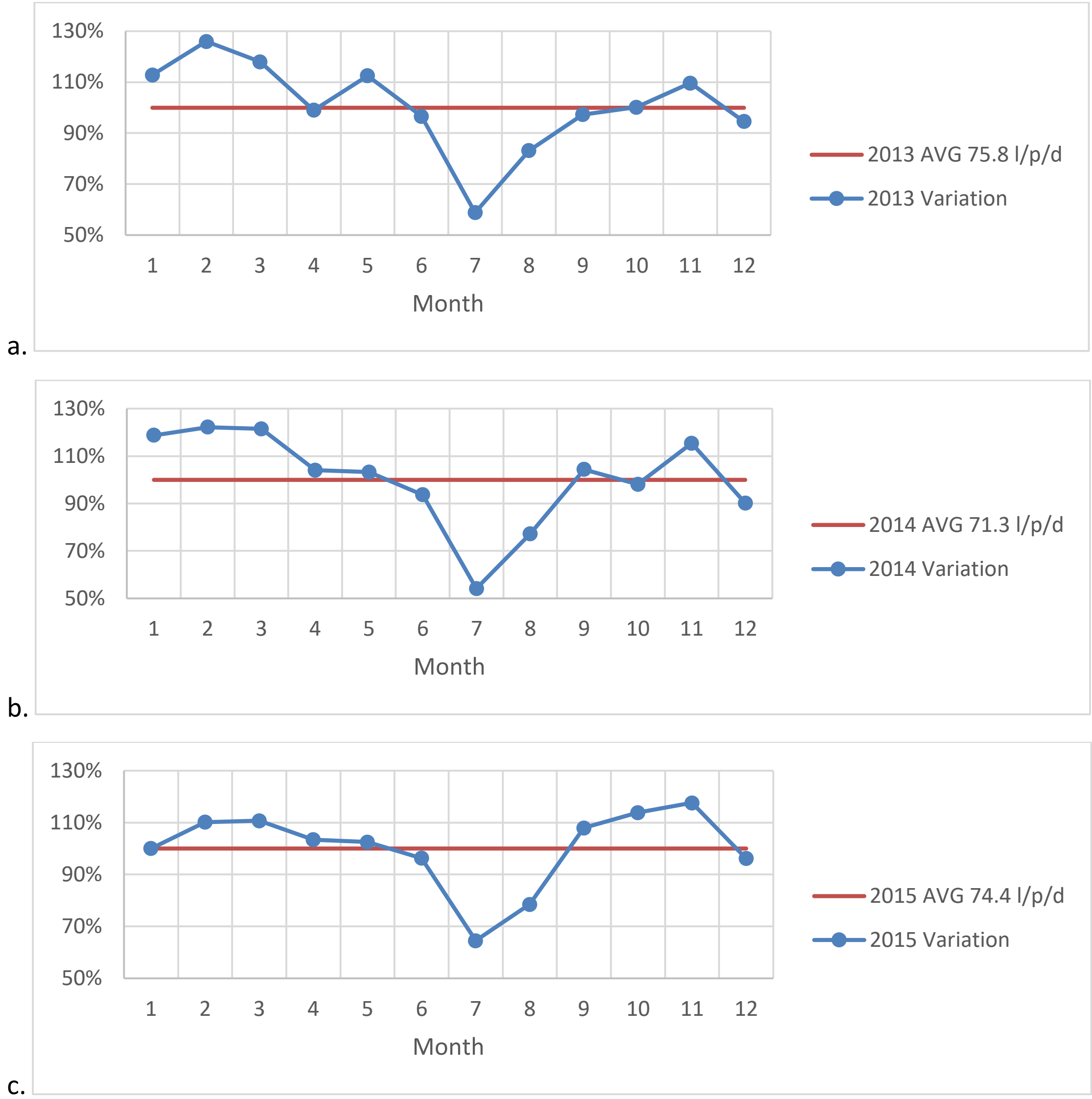
GRAPH 4.4 DIVISION OF THE YEAR IN THREE TIME PERIODS, ACCORDING GENERAL WEATHER CONDITIONS

Graph 4.5 shows the variation of water consumption for different months, as well as a year-to-year comparison for 2013, 2014, 2015 and 2016. The average daily consumption has remained on relatively the same level for all years of the measured period.



GRAPH 4.5 VARIATION OF WATER CONSUMPTION WITH COMPARISON BETWEEN MONTHS AND YEARS

As often the reviewed literature suggests, the average DHW consumption is lower in the summer period and higher in the winter period. The analysis of the data from the case building confirms that tendency as well. The pattern is repeated in all of the studied yearly time periods, regardless of the magnitude. The biggest variation from the average yearly consumption rate occur during the winter and the summer as can be seen on Graph 4.6. There again the repetitive pattern of fluctuation is visible for the three years.



GRAPH 4.6 MONTHLY VARIATION FROM YEARLY AVERAGE FOR A.2013; B.2014; C.2015

The graphs also show that there are some months with significantly lower consumption compared to others within the same season. That can be accounted for by the expected occupant absences during holiday periods associated with the different calendar seasons. These occurring fluctuation can be summarized by deriving monthly factors for each month. Those factors can help to predict the water consumption for a specific month of the year and thus help for energy calculations or sizing and control of DHW systems. The following equation is used to form the monthly DHW factors:

$$MF_i = \frac{DHW_i}{DHW_a}$$

EQUATION 4.1 MONTHLY FACTORS(3)

Where:

MF$_i$ *[-] is the monthly factor for a given month*

DHW_i [l/d] is the average domestic hot water consumption for the given month

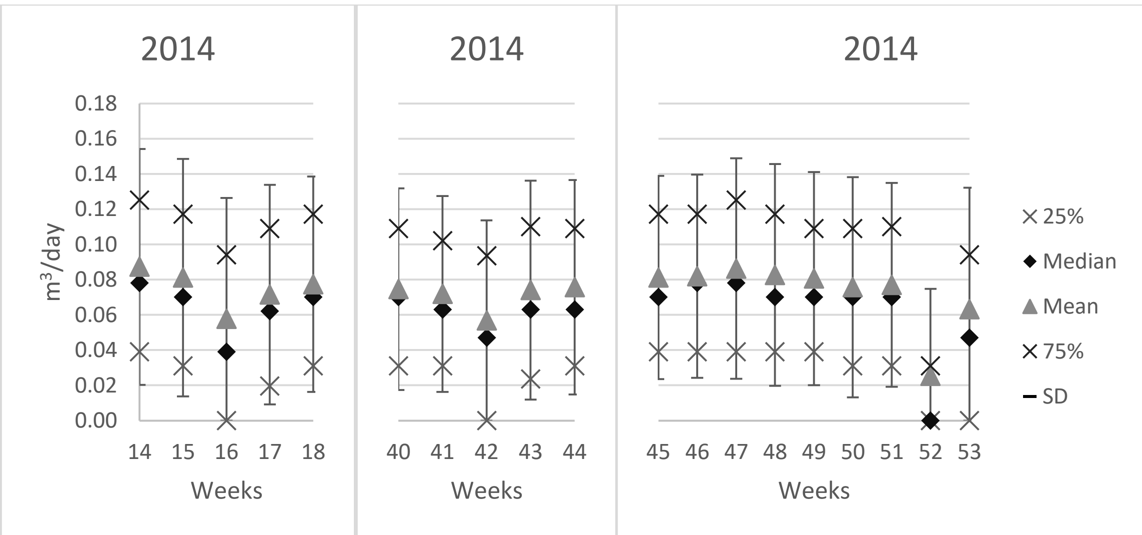
DHW_a [l/d] is the annual average domestic hot water consumption

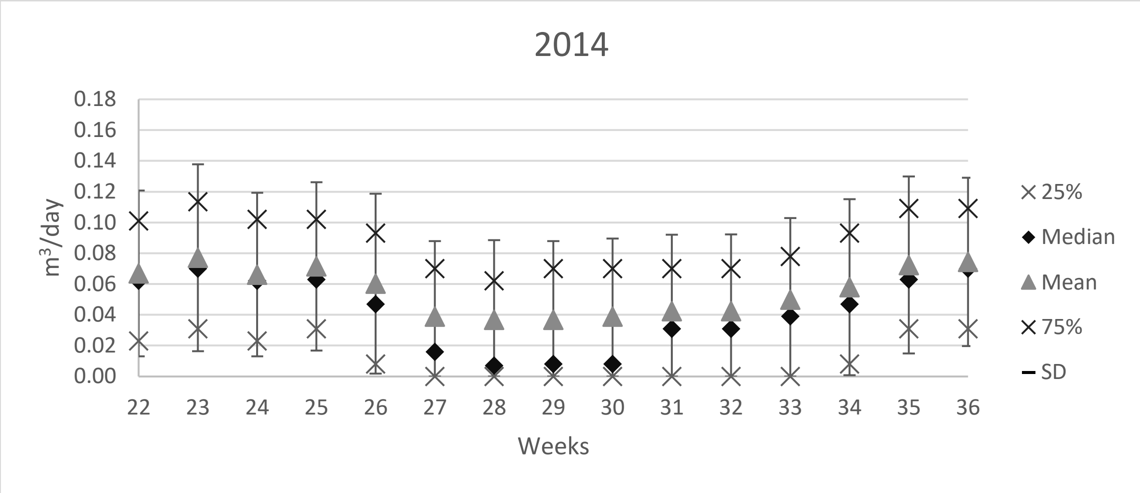
The results for the Monthly Factors (MF) are summarized in Table 4.2 for each month of the three analyzed years, as well as an average value of the three for any particular month. By representing the change in consumption throughout the year with monthly factors the number of people is not a variable that influences it since both the average monthly and yearly consumption are divided by the same number of people. Therefore, the factors can be applied for other buildings with a different number of people, however, if other factors are deemed similar.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2013	1.13	1.26	1.18	0.99	1.13	0.97	0.59	0.83	0.97	1.00	1.10	0.95
2014	1.19	1.22	1.21	1.04	1.03	0.94	0.54	0.77	1.04	0.98	1.15	0.90
2015	1.00	1.10	1.11	1.03	1.03	0.96	0.64	0.79	1.08	1.14	1.18	0.96
AVG	1.11	1.19	1.17	1.02	1.06	0.96	0.59	0.80	1.03	1.04	1.14	0.94

TABLE 4.2 MONTHLY CONSUMPTION FACTORS

The fluctuation in DHW use, also illustrated by the monthly factors is more significant in its magnitude, compared to the one in a similar study conducted for finish apartment block buildings (4). That could be specifically due to the type of building used for this analysis. Since it is a student accommodation building, it is highly likely that a great number of occupants are absent during school holidays compared to more general user groups in residential buildings. That could explain the very low use during July and the high use during February. Looking at the spread of daily consumption over different weeks in Graph 4.7, this tendency for lower consumption during holidays can be clearly observed, as it falls in line with the expected holiday periods.



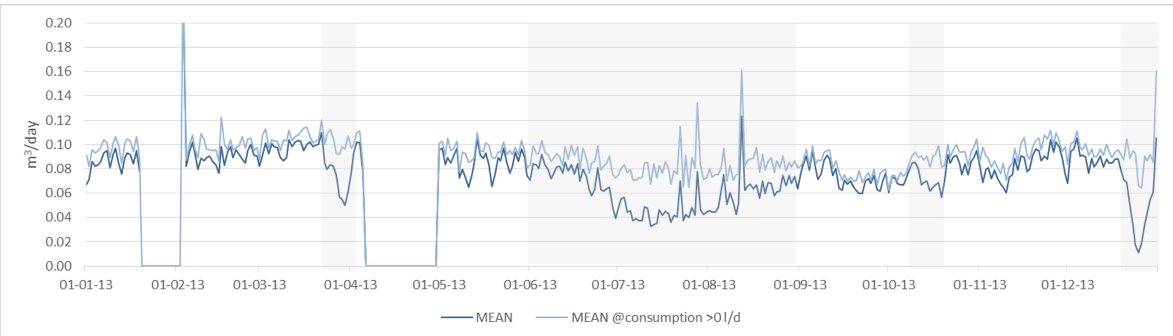


GRAPH 4.7 SPREAD OF DAILY CONSUMPTION FOR DIFFERENT WEEKS

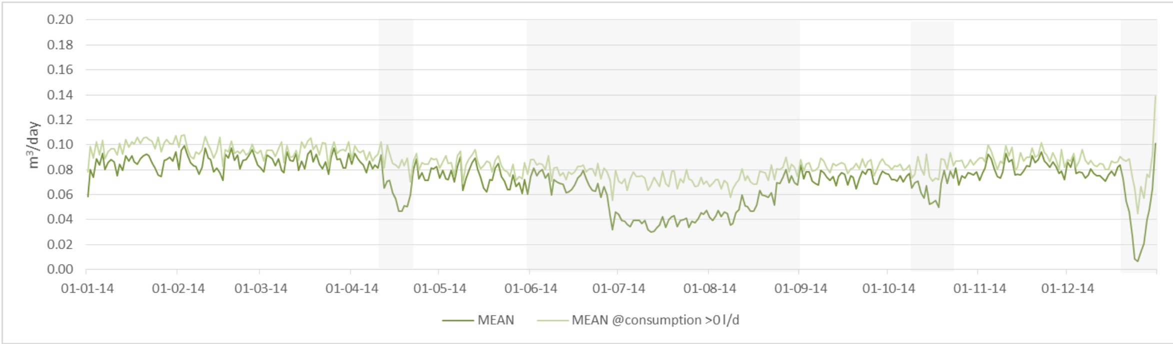
It cannot be concluded with complete certainty that the low consumption in the weeks during the holiday periods is due to absence of the occupants. However, it could be assumed that this is one of the more likely reasons for this tendency.

The average consumption and the MF represent the fluctuation in hot water consumption by taking into account all events, regardless of the magnitude. However, this could be misleading with regards to the actual consumption of water. It takes into account periods when people are absent and water consumption is zero, which does not indicate variation in the use, but variation in the use pattern. If the focus is to determine whether or not people use less water during different time periods of the year, a closer look needs to be taken at the DHW use when people are present in their homes and actually use water. That can be done by comparing the average daily water use based on the whole data set versus the average daily use for the data samples with usage value higher than zero. That comparison is strongly predicated on the assumption that when the daily consumption is zero, people are not present in their apartments. The assumption can be valid, as it is highly unlikely that people are not using hot water for a whole day when they are at home.

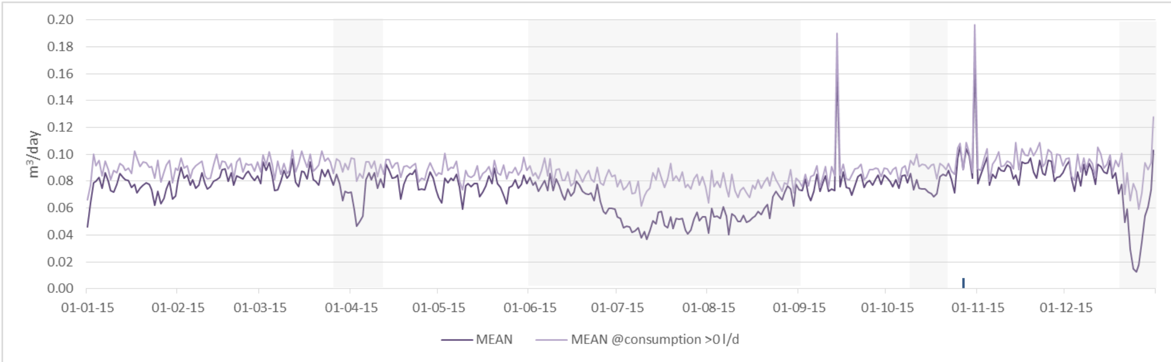
a 2013



b 2014



c 2015

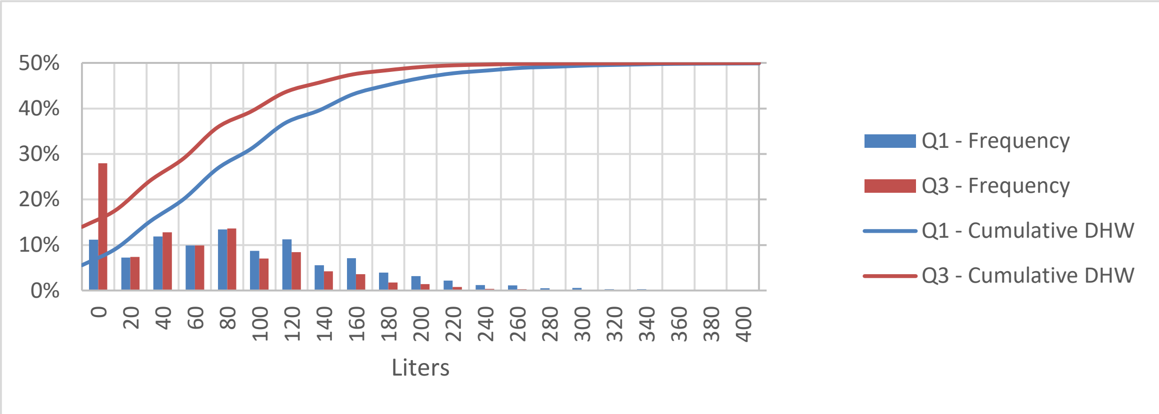


GRAPH 4.8 COMPARISON BETWEEN AVERAGE DAILY HOT WATER CONSUMPTION BASED ON THE WHOLE DATA SET VS. USE HIGHER THAN 0 M^3/DAY

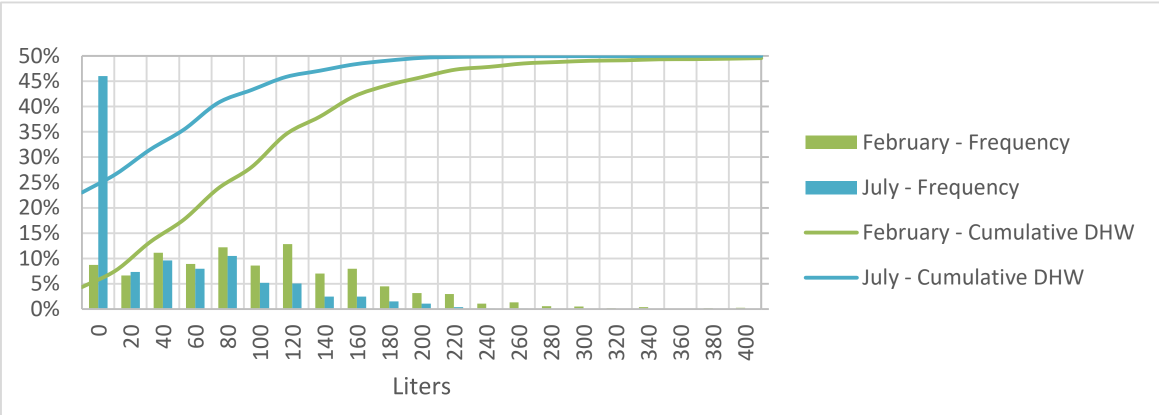
Graph 4.8 shows the average daily water consumption throughout the year, taking into account all measurements for the apartments for each day. A second plot is made, which shows the average daily consumption excluding values equal to zero, as it is assumed that no consumption in the apartments represents the absence of the occupants. The expected vacation periods are marked on the graphs and expectedly the average consumption in this periods is lower. From the graph, it can be concluded that the seasonal or monthly variation is smaller than what the variation based on the average daily consumption suggests because of the absence of the occupants.

The periods of absences are interesting on their own as less tapping increases the time duration for water circulation in the system and therefore the losses associated with it. Illustrating the absence of use for the periods of the year with highest and lowest consumption and comparing them can help to gain an understanding of the issue. Therefore, a cumulative graph and a chart for the frequency of occurrence of a specific water use is created to study that phenomenon. Graph 4.9a shows a comparison of the frequency of daily use of specific water volume for the first and third quarters, together with Graph 4.9b, a comparison of the two months with lowest and highest average consumption, respectively February and July.

a



b

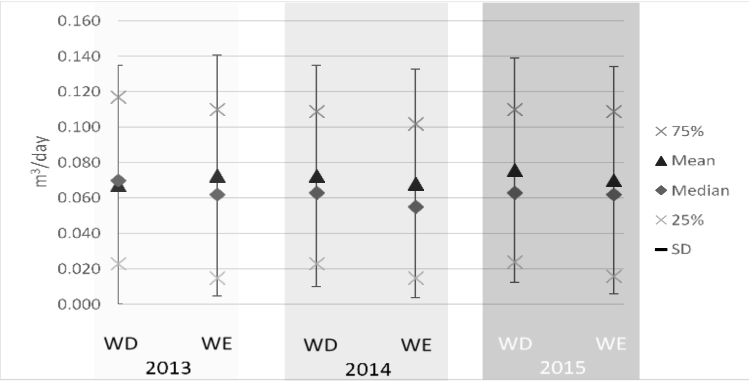


GRAPH 4.9 CUMULATIVE GRAPH FOR A. –THE FIRST AND THIRD QUARTERS; AND B. –THE MONTHS OF FEBRUARY AND JULY

It can be seen on Graph 4.9 that the occurrences when the use of DHW is zero are much more frequent in the summer period and the month of July than during the winter. As a result of that, the averages for both the quarter and the month are lower. It can also be noted that during the summer period people use smaller volumes of hot water per day more often than during the winter period. That is indicated by the frequency of daily use of different volumes of water. Whether that is due to increased volumetric use per tapping, the increased number of tapping per day, or possibly both, cannot be concluded with certainty from the plot. For such analysis, a data set with higher resolution would be required.

4.1.2 WEEKLY VARIATION

An aspect of the variation of the DHW use are the fluctuations during the week. In most general cases people have similar daily patterns during all weekdays and different during the weekends. That is why a comparison between average DHW use during the weekdays (WD) and weekends (WE) was done for each month of the four years. The results can be seen on Graph 4.10.



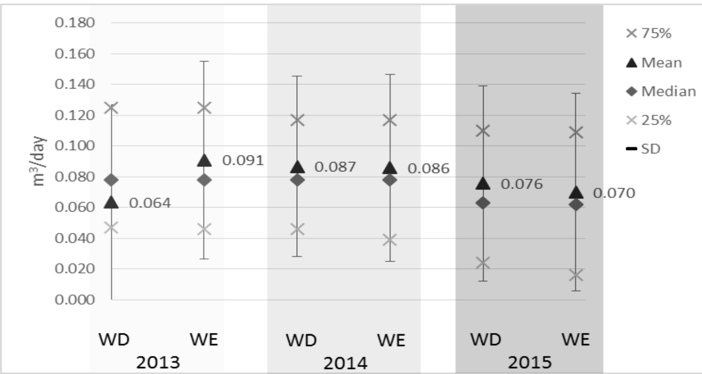
GRAPH 4.10 DAILY DOMESTIC HOT WATER CONSUMPTION FOR WEEK DAYS AND WEEKENDS FOR THREE YEARS

The results show that for the four years, from 2013 to 2016, the consumption rate on average is 6-8% higher during the weekdays than on weekends. Taking more detailed look at the daily use of hot water for week days and weekend by the distribution for each month of the year, it can be seen that during the summer period the consumption in the week days is generally higher than the consumption in weekends. That can be seen by the ratios of DHW consumption V_{WD}/V_{WE} in Table 4.3.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2013	0.98	1.12	1.08	-	1.09	1.09	1.16	1.15	1.12	1.1	1.05	1.01
2014	1.03	1.09	1.05	1.05	1.12	1.05	1.1	1.13	1.09	1.03	1.06	1.05
2015	1.07	1.03	1.08	1.16	1.1	1.06	1.11	1.07	1.14	0.98	1.07	1.15
2016	1.1	1.06	1.07	1.14	1.1	1.04	0.94	1.24	1.17	1.12	-	-
AVG	**1.04**	**1.08**	**1.07**	**1.12**	**1.1**	**1.06**	**1.08**	**1.15**	**1.13**	**1.06**	**1.06**	**1.07**

TABLE 4.3 MONTHLY VARIATION OF DHW USE WITH COMPARISON BETWEEN WEEKDAYS AND WEEKENDS CONSUMPTION

Looking at the actual consumption of water, disregarding the days with no consumption, as it was done previously, it can be seen that the average total daily consumption for weekdays is similar to the one for weekends for the years 2014 and 2015. The exception is 2013, which can be as a result of the large amount of missing data from the measurements for that particular year. However, the results are not conclusive enough to confirm that the actual use is higher in weekdays than in weekends, even though that seems to be the tendency for this case building.



GRAPH 4.11 AVERAGE DAILY WATER CONSUMPTION COMPARISON WEEKDAYS TO WEEKENDS, EXCLUDING CASES WHEN THERE IS NO CONSUMPTION (I.E. DAILY CONSUMPTION IS 0 M^3)

4.1.3 DAILY USER PROFILES

The available consumption data for the apartments at Grete Løchtes Gade 1 consists of daily measurements for each apartment, as previously analyzed. Using the daily consumption values alone cannot reliably provide a significant understanding of how and when occupants use hot water, and more specifically, help develop more detailed user profile that can further be used for sizing or modeling systems or computing energy demand in buildings.

However, several hourly consumption profiles have been developed in the past that have focused on analyzing the consumption of domestic hot water in dwellings. A study (1) was conducted that was based on a series of hourly measurements of DHW usage in several different houses – four in Tilst and three in Vejle. The results of this study can be deemed relevant and applicable to this case, due to the geographical, social and cultural similarities.

In order to analyze the data in an organized manner, measurements from the different days within a week were compared in a 24-hour timeframe. The results are presented in the following graph:

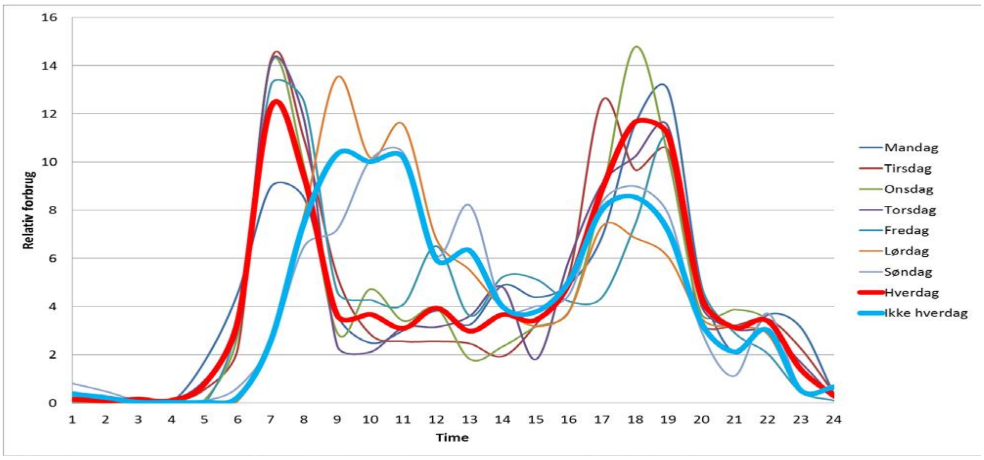


FIGURE 4.1 RELATIVE CONSUMPTION DISTRIBUTION FOR WEEKDAYS AND WEEKENDS (1)

The comparison between the different daily measurements shows that there is a certain difference between the consumption in the weekdays as opposed to the weekend. Nevertheless, as visible on the graph, the relative usage shows there is always a peak in the late afternoon/evening after 16.00 for both the weekdays and weekends. Another point worth mentioning is that even though the graphs summarize several data sets and days, there are periods during the day with no or close to no water consumption. Expectedly, the night periods is where that is most predominant. That is particularly important for this study, as it influences the energy consumption of system with circulation loops. Separate WD/WE profiles were derived from the houses located in Tilst and the ones in Vejle:

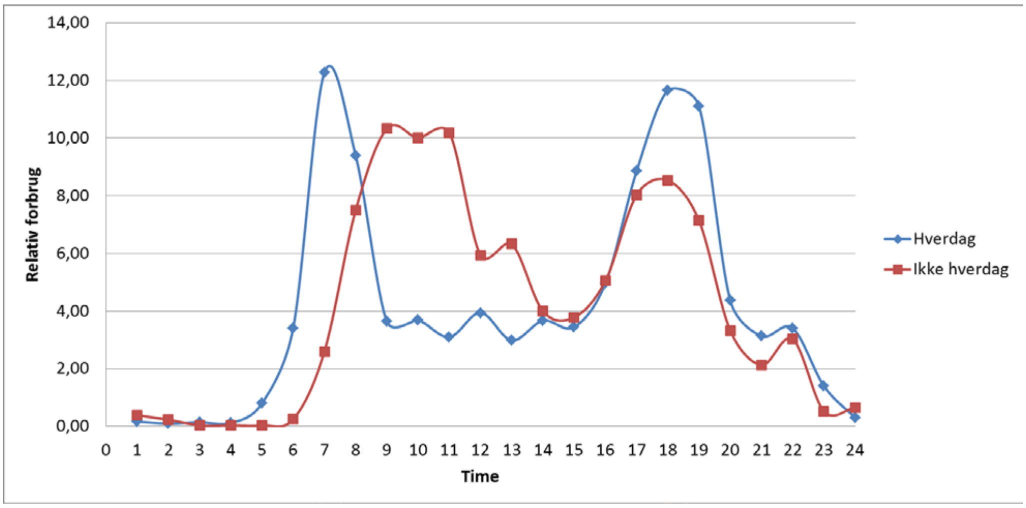


FIGURE 4.2 RELATIVE HOT WATER CONSUMPTION PROFILES FOR WEEKDAYS AND WEEKENDS (DATA FROM TILST) (1)

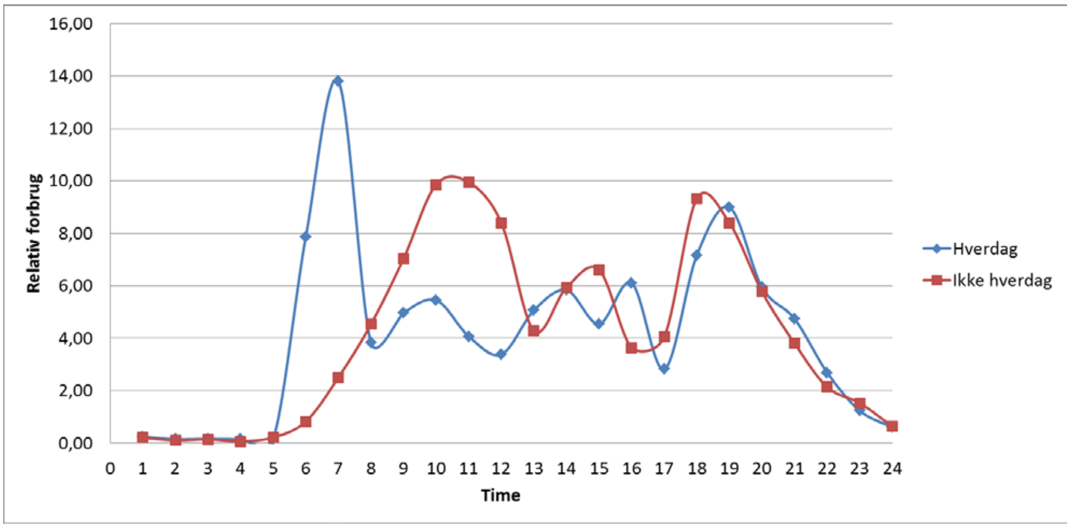


FIGURE 4.3 RELATIVE HOT WATER CONSUMPTION PROFILES FOR WEEKDAYS AND WEEKENDS (DATA FROM VEJLE) (1)

In both cases it can be observed that for weekdays there is a peak in consumption between the morning hours of 05.00 and 08.00 – 09.00 and also in the late afternoon hours from 16.00 – 17.00 until 20.00. Similarly, on the weekends, a peak occurs later in the morning around 10.00 – 11.00 as opposed to the early morning hours on the weekdays. A more significant difference in the two profiles is in the amount of hot water used on weekday evenings. That can possibly be attributed to other factors such as lifestyle or economic conditions, etc.

Since no reliable seasonal pattern was discovered from the analysis of the measurements, the two relative profiles created from the combined data of both the houses from Tilst and Vejle are produced for weekdays and weekends, as shown below:

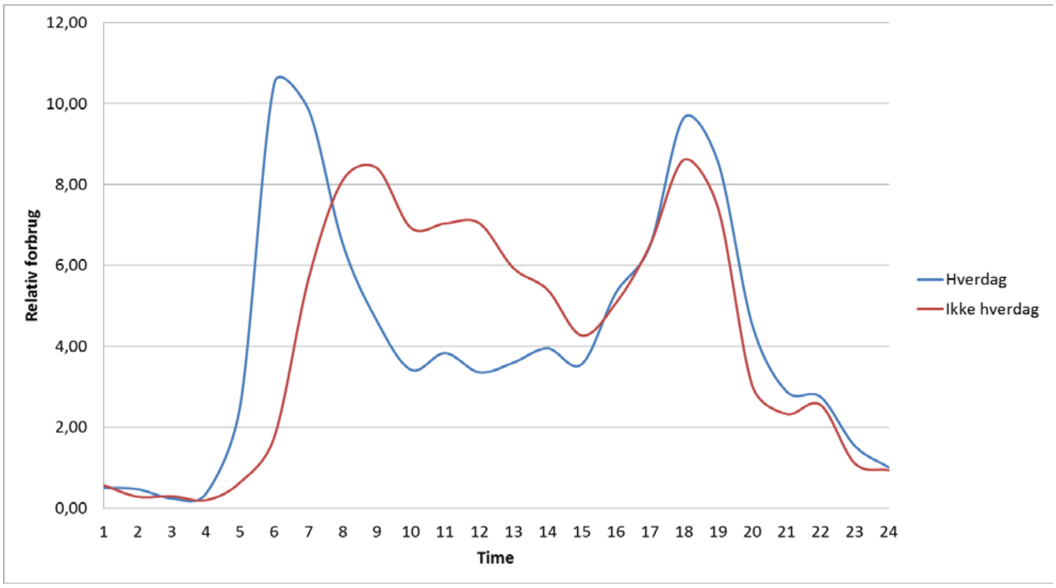


FIGURE 4.4 FINAL CONSUMPTION PROFILES FOR WEEKDAYS AND WEEKENDS (1)

In the DS-EN 15316-3-1 Standard – Systems for domestic hot water consumption patterns, there are several DHW profiles for different single family dwellings. Although they are more general and apply to different types of usage varying from very low for a single person to a very large, they also indicate some similarities to the usage pattern throughout the day – the difference being that they don't suggest a higher consumption in the morning before 7 and in the evening after 22.

Hourly consumption values were also developed (2) based on a number of hourly measurements for DHW taken from 86 Finnish apartments with 191 occupants. In the study, daily peak consumption for weekdays and weekends were identified, particularly in the morning and evening hours. According to their analysis, the morning peaks are occurring between 7.00 and 9.00 while the evening peaks were associated in between 20.00 and 22.00. In the time between 11.00 and 16.00 very low consumption was registered, with even less and nearly zero consumption occurring after midnight in the period between 1:00 and 5:00.

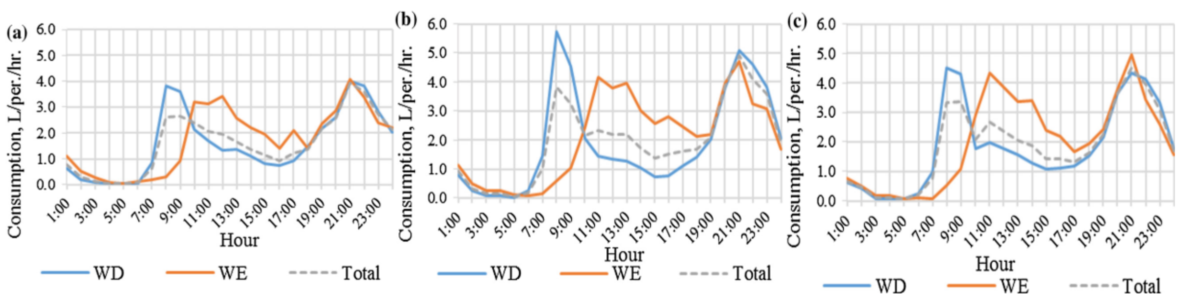


FIGURE 4.5 HOURLY CONSUMPTION PROFILES FOR DHW CONSUMPTION FOR AUGUST, NOVEMBER AND JANUARY (5)

Hourly average consumption profiles for domestic hot water are shown on the graphs above, for the months of August, November, and January respectively.

A similar tendency was observed in relation to the weekday and weekend peaks, where the morning peaks on weekends occurred 2 to 3 hours later, in the period between 10.00 and 13.00. The evening peaks were almost identical to the ones occurring during the weekdays (between 20.00 and 22.00). The hourly profiles were created taking into consideration the different group sizes occupying the apartments in order to develop universal consumption profiles that can be used for any number of occupants.

5 DOMESTIC HOT WATER SYSTEM

This chapter deals with one commonly used type of system for DHW and presents advantages and shortfalls of its general water delivery principles together with evaluation on its energy performance. A case study is created in order to conduct the evaluation and analysis. It is a simplification of a system in a reference building, described earlier in this paper.

5.1 CASE STUDY

The case study is developed using a multistory residential building in Aarhus as a reference. Some simplifications on the system are made in order streamline the evaluation and analysis process.

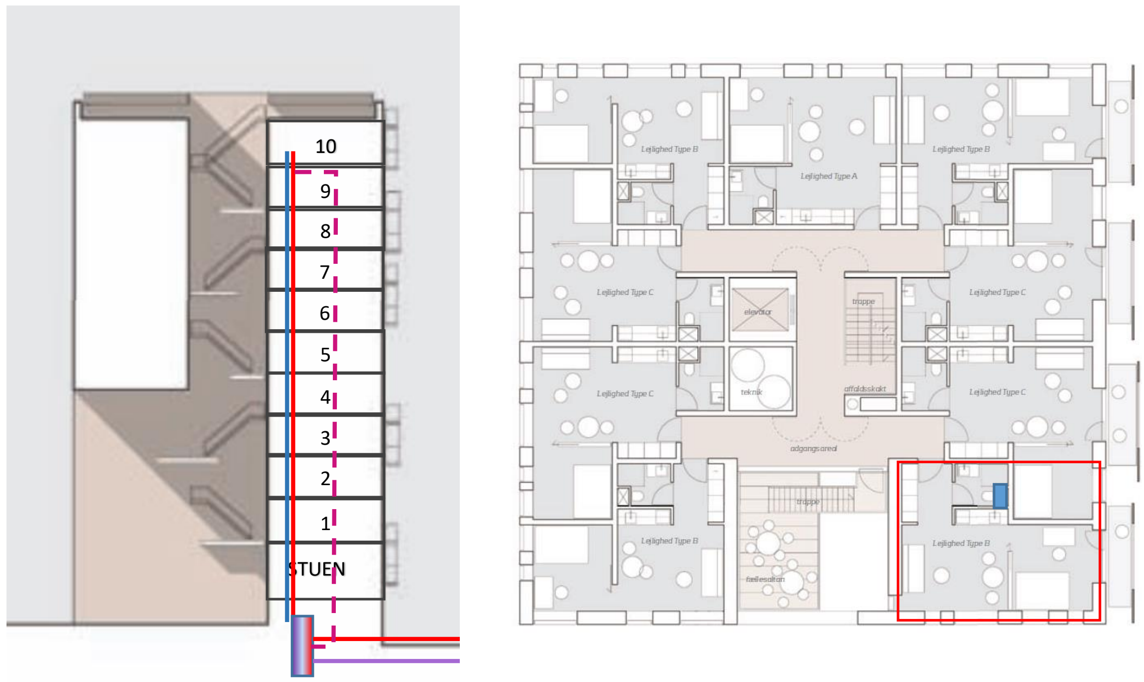


FIGURE 5.1 ILLUSTRATION OF DHW SYSTEM USED IN CASE STUDY

Figure 5.1 illustrates a schematic representation of the DHW system used for the case study. As a reference, the initial system is modeled after the actual system used in the dormitory building in Aar-hus. The building consists of a ten stories and 8-10 apartments on each level. However, for the purpose of simplification, the case study is limited to a stack of 10 apartments since it is assumed that one vertical branch in each service shaft services each similar stack of apartments, which will not affect the results for the purpose of this analysis. The heat source for the DHW system is district heating (DH). The coupling between DHW and DH is through a plate heat exchanger. The water temperature in the piping network is maintained using a circulation loop, in order to avoid long waiting time when tapping hot water.

The case study is developed using Aarhus reference building user group composition and derived hot water use from section 4 is used as input and definition of the consumption in the model.

Plate heat exchanger connected to District Heating

Drain water heat exchanger

FIGURE 5.2 COMPONENTS OF DOMESTIC HOT WATER SYSTEM AND DRAIN WATER HEAT EXCHANGER USED IN THE BUILDING

No exact technical information for the system was provided and therefore the case study was developed based on the information gathered by observations during a site visit.

5.2 INEFFICIENCIES IN THE SYSTEM

This chapters presents some of the reasons why a typical system can show some inefficiencies in performance. By discussing and analyzing those inefficiencies, the goal is to find possible solutions for improvements in the system.

Many energy systems are designed according to regulations and norms for their performance, but also according to comfort conditions that need to be met. The combination of those two factors often result in design solutions that are not optimal in terms of energy use or performance of the system. That compromise in some cases cannot be avoided. However, by taking a deeper look into how DHW systems operate, improvements on the performance could be made in a way that will allow the comfort conditions to still be met.

According to DS 439, the standard waiting time for the hot water to arrive at the tap in a household should be around 10 seconds at a flow of 0.2 l/s in order to both provide comfort and restrict water waste. However, that might be difficult to achieve in multistorey buildings due to physical constrains such as types of systems and lengths of the pipes in a network, etc. In such cases, hot water circulation can be implemented in order to avoid the long waiting time for the DHW to arrive at any given tap within the building. Additionally, circulating the water in the system for the purpose of maintaining the required temperature prevents large amounts of water being wasted during the waiting time periods, if the like instance occur. The reference building used in this case study uses circulation loop and therefore it is of interest to see how that affects the performance of the system.

For the purpose of user convenience and comfort however, circulation systems present several problems. Some of them are the additional energy required to run the circulation pump, the heat losses from the circulation pipes, as well as high return temperatures for the DH water.

5.2.1 PUMPING OF WATER

Often DHW is driven in the system by the pressure of the incoming water flow and/or a pump. In the cases with lengthy pipe systems, where the pressure of the flow cannot overcome the static and dynamic pressure resistance in the system, pressure is increased most commonly by a pump. That results in little to no energy use for running the water with the required flow when tapping, compared to the total energy use of the system. However, in systems with circulation a pump is needed to recirculate the water in the pipe network through the heat source, to ensure sufficiently high temperatures at the far ends of the system. That presents additional energy use for running the pump, even though no tapping of water occurs. That inefficiency in the system, howbeit, can constitute a small fraction of the total energy requirement for DHW in a building system, around 2-3% for houses, multistory and commercial buildings, according to a report done by the Danish Building Research Institute in 2009(1). Nonetheless, it is evaluated by simulation for the case study building to estimate the fraction in this case.

5.2.2 HEAT LOSSES

Heat transfer occurs when there is a temperature difference between two physical systems. The higher the temperature difference the higher the heat transfer, as derived by Fourier's law of heat transfer.

$$\dot{\boldsymbol{Q}} = \boldsymbol{A} * \boldsymbol{U} * \Delta\boldsymbol{T}\ [\boldsymbol{W}]$$

EQUATION 5.1 FOURIER'S LAW FOR THERMAL CONDUCTION

Where:

A [m^2] – area of conduction

U [w/m^{2}K] – conductive heat transfer coefficient (the U-value of the pipe is adjusted for the internal and external area of the pipe by the use of logarithmic mean diameter)

ΔT [K] – temperature difference between two physical systems

$$\dot{\boldsymbol{Q}} = \dot{\boldsymbol{m}} * \boldsymbol{C_p} * \Delta\boldsymbol{T}\ [\boldsymbol{W}]$$

EQUATION 5.2 FOURIER'S LAW APPLIED TO A FLOW

Where:

m [kg/s] – fluid mass flow

C_p [J/kgK] – specific heat capacity of fluid

ΔT [K] – temperature difference between two physical systems

As the temperature in the system must be maintained at 50°C, this results in significant heat losses from the piping system to the surroundings, whether that is the indoor areas with 20°C or unheated spaces with lower temperatures. The heat loss also increases with the length of the pipe network as the volume of the contained water increases as well, and additionally, with the increment of circulation cycles in the system. That inherited inefficiency of DHW systems with circulation results from applied requirements for the temperature in the system associated with health and safety, and the comfort of the occupants. Common misconception among professionals is that the heat loss from the system to the indoor is utilized as heat gain for the space, as it reduces the heating demand for the building. However, that is not always the case as discussed in (1) and (6). Only part of the energy is utilized as free heat in the building and that is only when the building needs heat; the rest of the energy is lost and is therefore unrecoverable.

5.2.3 INEFFICIENT COOLING OF RETURN WATER

Other inefficiencies of the system are related to the high return temperature on the circulation loop. Whether the system is coupled to district heating through a heat exchanger or a storage tank with internal heat exchanger connected to an energy source, the issue persists. When water is returned to the energy source at a high temperature (around 40-50°C), this does not allow for an efficient energy extraction from the source. As heat transfer will last only until temperatures in the two systems equalize, the temperature on the return water on the primary side can only cool down to the temperature of the supply temperature on the secondary side. Taking the setup used in the case study as an example, the water temperature on the secondary side is at minimum 38°C, which means that on the primary side, at a given flow, the water can be cooled down to a maximum of 38°C for 100% efficiency of the heat exchanger. In reality, that temperature is much higher, due to higher set flow rate on the primary side and lower efficiency of the heat exchanger.

Some district heating providers charge the consumers based on the volumetric use of water from the system, and others charge based on unit delivered energy. Regardless of the method of billing the costumers the inefficiency in the system is in place with the only difference being that in one case the inefficiency is at the consumer end and the other it is at the providers end. Often insufficient cooling of the district heating is penalized by additional charges by the providers. Therefore, the DH return water temperature could potentially be reduced by lowering the return water temperature on the secondary side and thus promoting a bigger heat transfer between the two water circuits. Utilizing the DHW heat in a more efficient way can be a benefit to both the DH and the users.

5.3 GOAL PARAMETERS

The results of the system performance are expressed by several parameters. The total energy consumption, as a combination of the energy consumption at the various components of the system presented in order to evaluate how efficiently the system delivers energy to the end user. Furthermore, the same energy representation is used to evaluate the amount of heat loss for the system, as it is assumed that it is the difference between the produced and the delivered energy.

Water temperature at different components helps to identify the inefficiencies in the system by giving an indication on where the losses occur. Also how the water temperature changes throughout the component, which can help to find optimal position of temperature sensors for activating the circulation loop in the system. Additionally, varying input parameters and monitoring of water temperature at various components enables fine tuning of the system. An example of such analysis is that by changing the placement of the temperature sensor for activating the circulation loop, and monitoring the temperature in the vertical branch and circulation loop, a better alternative solution could be found.

As previously discussed, an inherited inefficiency of DHW systems with circulation is the high return temperature at the energy source. Therefore, that is one of the parameters that is investigated and more so, how it is affected by changes in other parameters of the system and different systems setups.

5.4 SYSTEM DESCRIPTION AND BOUNDARY CONDITIONS

This chapter contains a description of the general inputs for the simulation model and sets the boundary conditions used for the analysis.

A simplified simulation model is created to establish a benchmark for comparing results of different DHW systems. Simulation tool PolySun is used for that purpose. Different criteria will serve as the basis of the comparison between the results, with some of the primary parameters being evaluated such as heat losses, flow rates, return temperatures, etc. The software is capable of computing multiple relevant parameters involved in the utilization of energy and the production of domestic hot water in a defined setup. The software makes a dynamic simulation on the basis of the provided one node model, where the time step can be set as low as 5 seconds. Results presented graphically can be with high resolution as a function of time and duration. However, Input parameters and results in a tabular format can only be presented in average hourly values.

Due to insufficient information about the system itself, most input values and design decisions are estimated or based on other available sources or standards from literature.

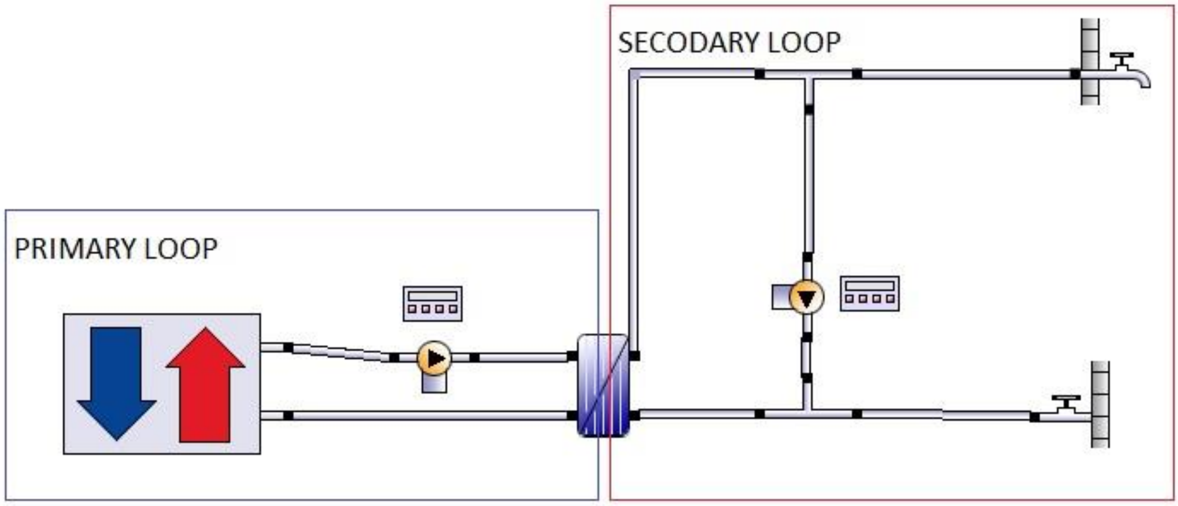


FIGURE 5.3 PRIMARY AND SECONDARY LOOP IN THE SYSTEM

Figure 5.3 illustrates the simplified system set up – DH is used as an energy source for the heating of the cold water, which is then delivered when there is a demand for DHW or circulation. If not used at the tap, the DHW is cycled through the circulation system controlled by another pump. The circulation pipe is assumed to be connected to the supply pipe before the furthest tap (on the tenth floor).The demand hot water temperature at the tap is defined at 50°C and the supply cold water temperature is assumed to be 10°C. The length of the pipe network to the furthest tap is assumed to be 40m from the heat exchanger to the connection point of the hot water supply pipe and the circulation pipe. It is assumed that the pipes are made out steel and are insulated with the minimum insulation stipulated in DS 452(7), as referred in Danish Building Regulations 2010 (BR10)(8) The requirement is namely, for pipes located in unheated spaces with temperature greater than 5°C, the value corresponding to class 4 and for heat exchangers and hot water storage tanks in unheated spaces with temperatures greater than 5°C – class 5.(7) Determining the thickness of insulation can be seen in Appendix C .

	U-value for pipes [W/mK]	**U-value for plane surfaces [W/m^{2}K]**
Class 4	1.5 * D_{ep} + 0.16	0.49
Class 5	1.1 * D_{ep} + 0.14	0.35

TABLE 5.1 INPUT PARAMETERS FOR PIPE HEAT LOSS ACCORDING TO NORM

Where:

D_{ep} is the external diameter of the pipe.

The heat exchanger is a plate heat exchanger and has a heat transfer capacity of 5000 W/K and heat loss coefficient trough the housing of 1 W/m^{2}K. It is chosen from PolySun's product database, in accordance with the calculations done for the maximum power output of the heat exchanger based on calculated load and temperature set point. Detailed calculations can be found in Appendix D .

(7)(8)

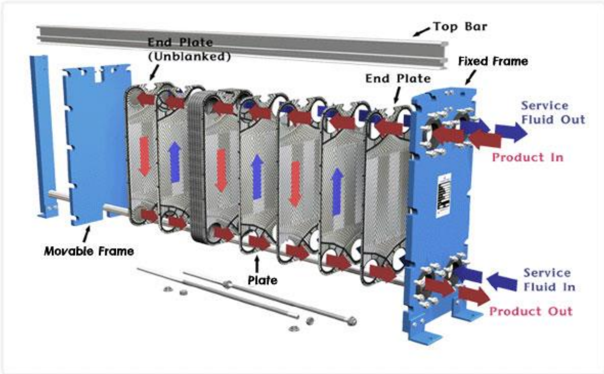


FIGURE 5.4 ILLUSTRATION OF A PLATE HEAT EXCHANGER (PHE) (9)

Figure 5.5 represents the initial system design (Benchmark System) created in Polysun, defined by two active loops. At the energy source, DH is used with design values for the supply and return water.

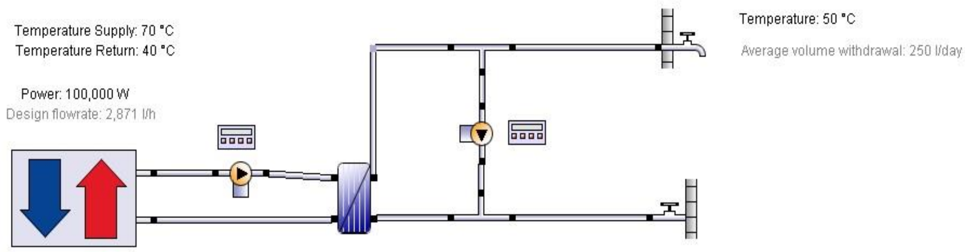


FIGURE 5.5 INITIAL SYSTEM DESIGN

Heat transfer occurs in the heat exchangers. The efficiency of the heat exchanger is predetermined and is taken from the manufacturer's database. The heat demand is defined by the required mass flow and temperature rise on the secondary loop. Then the mass flow on the primary side is regulated in order to provide the required heat and to return at a temperature lower than the maximum allowed return temperature of 40°C.

The mass flow on the primary side is proportional to the mass flow on the secondary side, as the presented heat balance equation suggests. This simplified heat balance equation describes heat transfer between two systems at a steady state condition and does not account for heat losses in the two systems or the heat exchanger to the surroundings.

$$Q_p * \eta = Q_s$$

$$\dot{m}_p * Cp * \left(T_{S_p} - T_{R_p}\right) * \eta = \dot{m}_s * Cp * \left(T_{R_s} - T_{S_S}\right)$$

$$\frac{\dot{m}_p}{\dot{m}_s} = \frac{\left(T_{R_s} - T_{S_S}\right)}{\left(T_{S_p} - T_{R_p}\right) * \eta}$$

Where:

$\boldsymbol{Q_p}$ [W] is the energy output on the primary side

$\boldsymbol{\eta}$ [-] is the efficiency of the heat exchanger

$\boldsymbol{Q_s}$ [W] is the received energy on the secondary side

EQUATION 5.3 HEAT TRANSFER FROM PRIMARY LOOP TO SECONDARY LOOP THROUGH HEAT EXCHANGER

The secondary loop includes the supply pipe and the circulation of hot water. Another pump regulates and maintains the hot water temperature in the circulation loop. The water temperature in the loop is controlled via controller using temperature sensors to determine the required flow of the circulation pump. The sensors detects when the temperature in the loop falls under the reference temperature set point, which in this case is set to be equal to the hot water demand temperature of 50°C. The circulation pump is activated on demand when a temperature difference between the water temperature in the loop and the set point occurs. A temperature differential is allowed between the water temperature in the circulation and the demand temperature, since a lower temperature on the circulation minimizes the heat losses. The cold water temperature is defined at 10°C by using the standard Northern Europe profile from the Polysun database, which is also in line with the design conditions typically used in Denmark. It should be noted that the defined temperature range in the profile is the difference between the mean cold water temperature and the higher temperature during the year. Warmest month is the month with the highest cold water temperature.

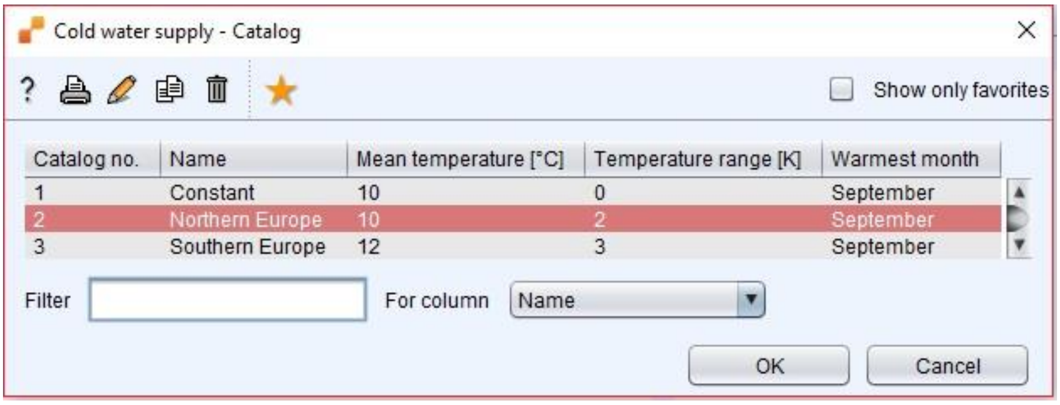


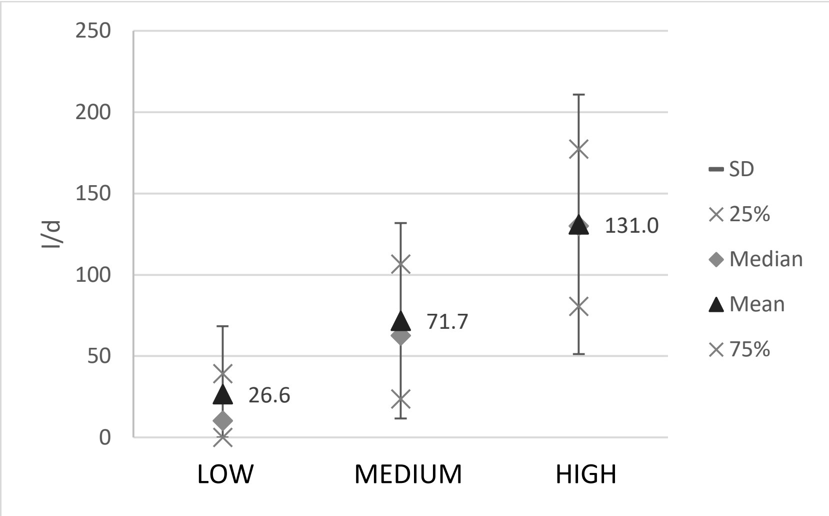
FIGURE 5.6 COLD WATER SUPPLY SETUP IN POLYSUN

5.4.1 LOAD PROFILES

This chapter introduces the DHW load profiles used for the simulations of performance of selected DHW systems. As discussed previously in Chapter 4.1, the use is analyzed based on data for individual apartments, disregarding the number of occupants. That results in an average daily hot water consumption of 74.6 l/d.

5.4.1.1 AVERAGE DAILY USE AND MONTHLY VARIATION

Division in three subgroups of daily hot water use is done in order to allow for bigger variation of the input, thus allowing to simulate for scenarios, which are assumed to be most likely.



GRAPH 5.1 LOW, MEDIUM AND HIGH DAILY USE PER APARTMENT, DERIVED FROM MEASURED DATA.

The derived user profiles are based on a relatively small data set of 99 apartments over a period of 3 years, which does not allow for considering them representative for all cases. Larger data set would make the uncertainty of the results smaller and therefore more conclusive, which is not the case here. However, due to lack of more representative data, that is used in the latter stage of the project for simulating energy performance of DHW system.

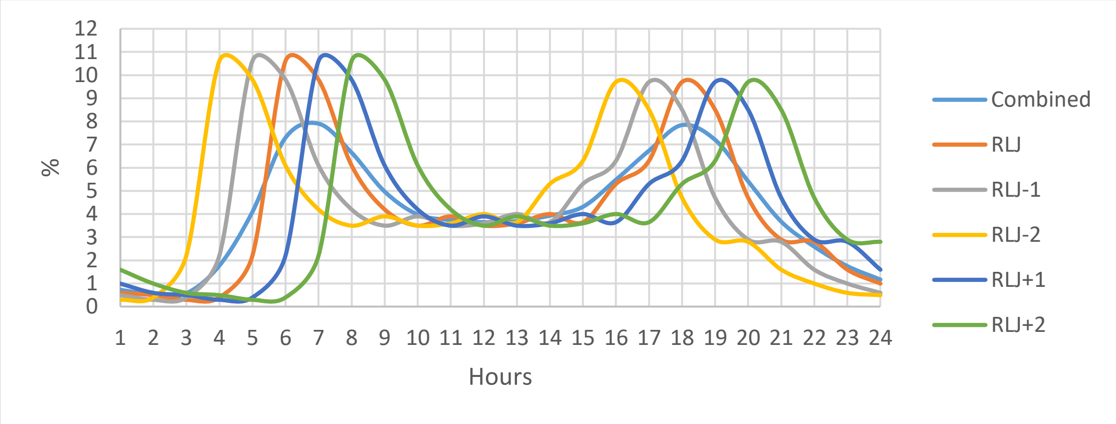
As an input for the simulation tool used for this case study, average monthly consumption is required. As already established in the section 4.1.1*,* the average monthly consumption varies throughout the year. Therefore the derived monthly factors are applied to the average consumption of each profile to represent that variation in the input for the simulations.

5.4.1.2 HOURLY PROFILES

Due to the limitations for the Polysun software, the system design does not allow for multiple different daily profiles to be selected when simulating a system performance. The DHW demand is distributed equally regardless of the number of users the system is designed for, which means that depending on the hourly schedule for DHW use, there might be times with no consumption. This might be unrealistic in a multistory building with many occupants following different schedules.

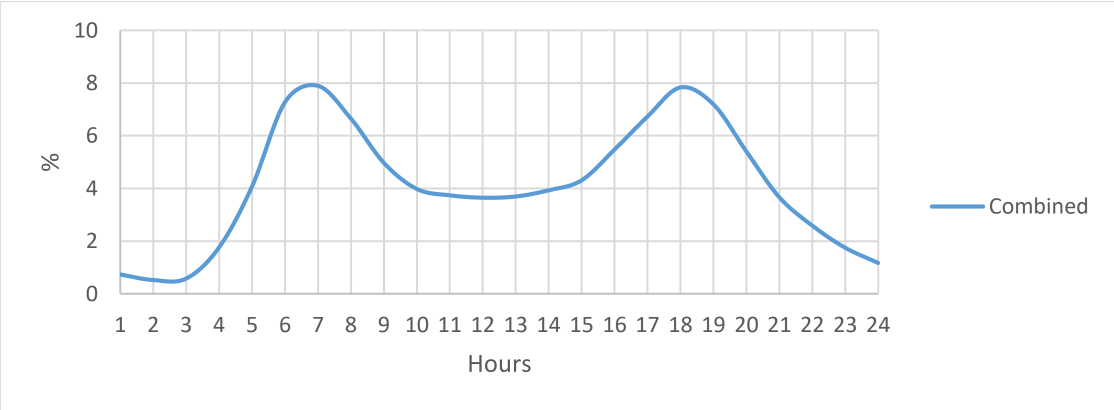
In order to avoid using a schedule with more drastic variation in DHW consumption and periods with no usage, a modified daily profile is created for the purpose of simulating different fractional use all across a 24-hour period. As a reference, the profiles presented in the study discussed previously (1) based on a series of hourly measurements of DHW usage in several different houses in Tilst and Vejle are taken. The daily distribution is shifted with an offset of 1 and 2 hours on the x-axis, creating a total of 5 different daily schedules.

It is defined that out of the 10 different users the system is designed for, 4 are following the standard daily schedule, 2 are following each the -1h and the +1h offset schedules, and 1 is following each the +2h and -2h offset schedules.



GRAPH 5.2 HOURLY FRACTIONAL PROFILE FOR A DANISH HOUSEHOLD WITH AN OFFSET VARIATION

The combined profile represents the DHW use for all the 10 users following their respective schedule as a fraction of the total daily consumption within a 24-hour period.



GRAPH 5.3 COMBINED FRACTIONAL HOURLY PROFILE DHW DISTRIBUTION

5.4.2 STANDARD TEMPERATURE SETPOINTS

Domestic hot water systems typically operate with water temperatures above 50°C. That is not only to ensure the comfort levels at the user end but also to prevent the growth and development of harmful bacteria. Often building codes regarding domestic water are developed taking preventive measures in mind. One of the types of bacteria, most often mentioned in codes and norms is Legionella. Legionella is a bacteria that lives and grows in different environments including water. The bacteria can cause Legionella disease and flu-like illness called Pontiac fever. Since one of the mediums where the bacteria lives, grows and develops is water, domestic water systems have been under regulation, in order to prevent infections.

The bacteria can be treated by means of chemical solutions or thermal methods. Therefore, regulations regarding operational temperatures in domestic water systems across the world have been established accordingly. The European code on which also the Danish code is based sets certain set of required minimum temperatures for DHW systems and hot water storage tanks with one of the main focus being Legionella prevention.

Hot water storage tanks commonly present ideal growth conditions for the Legionella bacteria, as they can enable relatively large volumes of hot water to stagnate and lower its temperature over time. According to "Legionella and the prevention of legionellosis"(10), the ideal growth temperature range for the bacteria is between 32 to 45 °C. Since these temperatures also fall within the range of DHW temperatures used in households, DHW standards and regulations usually specify a value of 60 °C as a minimal temperature for storing DHW and 50 °C to 55°C as the minimal temperature running in the pipe network and delivered at the tap.

Furthermore, as mentioned earlier, there are numerous methods and solutions to deal with potential bacterial proliferation, since constantly high temperatures alone does not prevent the risk of Legionella growth in DHW systems.(10) Chemical treatment, UV light disinfection methods and water tap micro-filters are among the most common solutions, but they present other issues and complications (chemicals, additional costs for maintenance, etc.). That is why most international standards and regulations emphasize on maintaining the DHW in a certain temperature range as a higher priority.

5.5 LIMITATIONS

There are several limitations to the tool of choice (Polysun) for simulating system performance. The software does not allow for specifying multiple consumption component (water demand component). That limits the input to the application of a single hourly load profile. The daily water consumption of several apartments (in this case 10) is added up and an hourly profile is applied to the total water consumption of the building. Since one hourly profile will not accurately represent the DHW use of multiple apartments, an adjusted standard hourly profile is used. The hourly profile described in section 5.4.1.2 Hourly profiles is developed to allow for the diversity of water use, but simplified and using one hourly profile.

The simulation tool is based on a one node calculation model, which means that the conditions in a component are the same throughout the volume of the component. For example the water temperature in a pipe might be different in the beginning of the pipe compared to the end of the pipe. The one node model however is deemed sufficiently accurate for the purpose of some parts of this analysis, which is to observe how and when inefficiencies in the system occur and discuss possible solutions and evaluate their feasibility.

5.5.1 WATER WITHDRAW

Hourly profiles are defined as fractional values for each hour of the day. Employing this method is a common practice amongst professionals when evaluating DHW systems' performance. Furthermore, higher time resolution for DHW use is rarely used for system design and it generally has not been studied extensively and profiles have not been developed.

Using the specified daily water use in combination with the fractional hourly use, the average water consumption for each hour of the day is defined. One of the simulation inputs is the flow rate at the tap, when tapping. The definition of specific hourly water demand is being met in the beginning of each hour of simulation, continuously until reaching the required value. The time needed for that can be calculated using the specific hourly demand and the water flow rate when taping. That means for example that if at a given hour there is a demand of 10 l at a flow rate 8 l/m = 0.13 l/s (typical flow rate for shower faucet) the demand will be reached in little over 78 sec. the rest of the hour would be without taping as the demand for it is already reached. Obviously, that does not represent the reality in the most accurate way, as there could occur several tapings with smaller duration in different times within the one hour time frame. However, this is a simplification in the software, which cannot be avoided. Furthermore that simplification does not present a major issues when simulation for system energy performance, which is also what the chosen software is intended for.

5.6 SYSTEM PERFORMANCE

This chapter introduces the results of the simulation of the standard system in the context of selected parameters. The performance is evaluated with regards to the expected inefficiencies in the system, mentioned earlier. All parameters and variations are evaluated and compared for comfort and energy demand being met. In PolySun, the assessment for fulfilling the energy demand, which also indirectly indicates whether the temperature set point is met, is performed automatically and if not met, a warning message appears. The assessment on meeting the energy demand is done within allowed deviations. The allowed deviation from the set required temperature and/or delivered energy is 5% for 5% of the time. As an example if more than 95% of the required energy (Energy is expressed as a function of flow rate and temperature) is delivered for more than 95% of the time, the software considers the demand as met. Since for DHW systems, the water flow is at a predefined rate, the variation in energy is due to variation in temperature.(11)

5.6.1 Results

This chapter introduces the results for set of simulations done for a DHW system model, where sets of simulations are made with selected parameters varied. The full table with the variations for the simulations can be seen in Appendix F .

5.6.1.1 Placement of temperature sensor for control of water circulation

The first set of simulations observes the change in energy use when the temperature sensor for the activation of the circulation loop is in different positions. Commonly the temperature sensor is close to the circulation pump due to practical reasons. In such setup all components are close to one another, situated in the technical room of the building make them easily accessible by service personnel. Such placement is illustrated by Figure 5.7 :

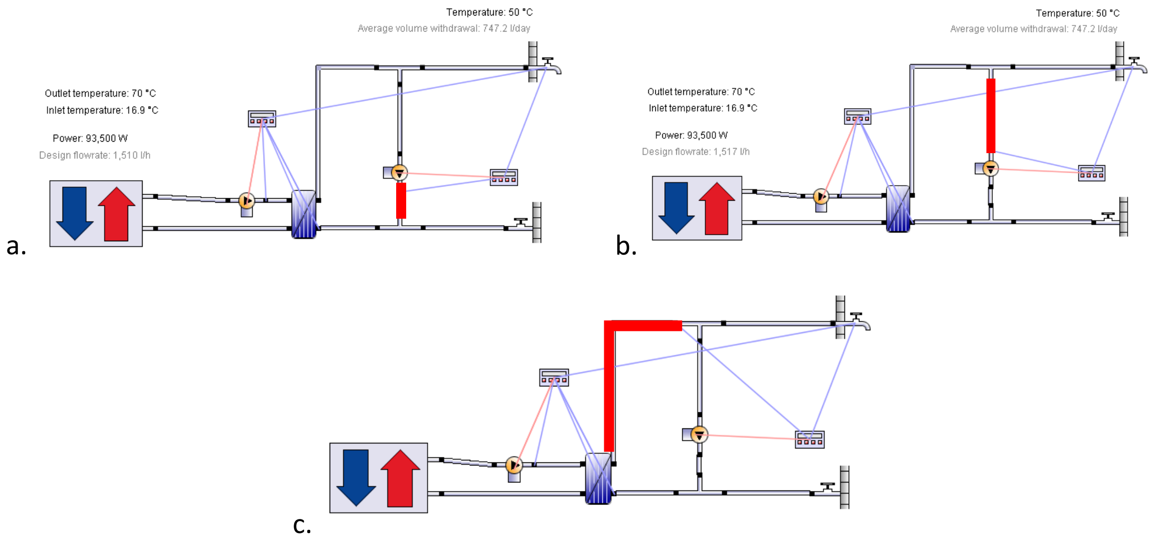
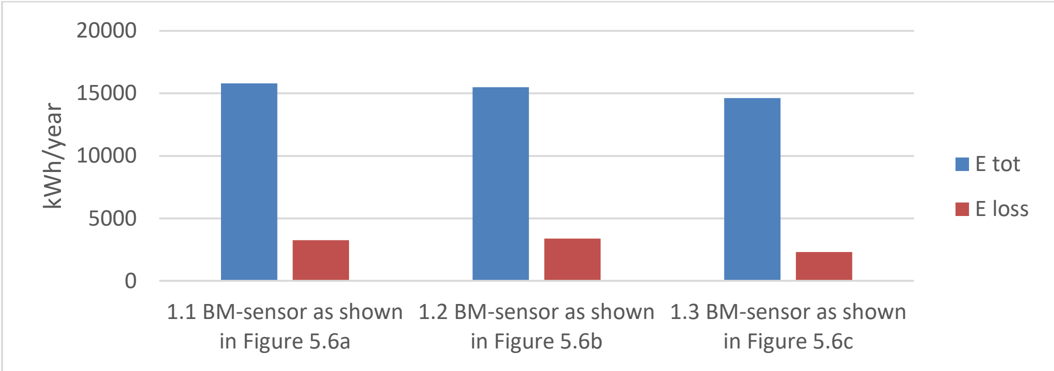


Figure 5.7 Temperature sensor location presented in the three cases

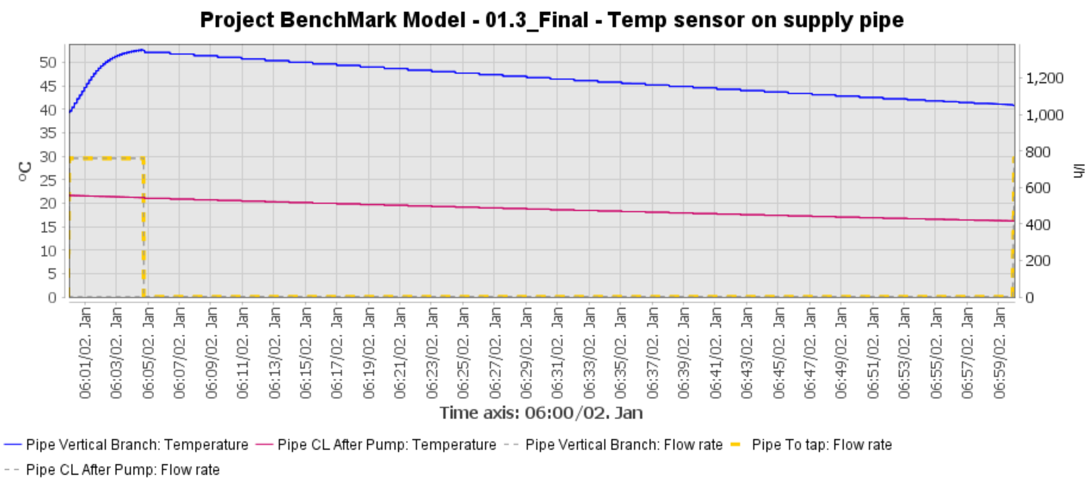
As already discussed, PolySun uses one node model, and therefore the actual location of the sensor on the pipe is irrelevant for this set of simulations, as the temperature is assumed the same across the entire pipe length.

The convenience of placing the temperatures sensor close to the pump results, however, in greater water volume with high temperature contained in the pipes, which in turn results in greater heat loss. The required water temperature should be maintained until the connection point with the tap. In the standard setup, with the temperature sensor placed after the pump, the water needs to circulate all the way to the sensor, in order for the system to deactivate circulation. This results in filling the circulation pipe with water with high temperature, which is passed the user end of the system.



GRAPH 5.4 COMPARISON BETWEEN ENERGY CONSUMPTION AND HEAT LOSS FOR THREE SETUPS WITH DIFFERENT PLACEMENT OF TEMPERATURE SENSOR FOR ACTIVATING CIRCULATION

The results show a reduction of the total energy use of the system, by the change of the placement of the temperature sensor further away from the end of the circulation loop, with energy demand still being met. The reduction on the total energy is by 7% on simulation 1.3 compared to 1.1. Furthermore the heat loss from the pipes is reduced by 5% from 21% on case 1.1 to 16% on case 1.3. The conducted set of simulations confirms that the energy use of the systems is effected by the placement of the temperature sensor, used in the control of the circulation loop, with the comfort conditions satisfied. Aditionally, a more detailed simulation is done with the pipes being divided in several nodes and using one daily profile. This simulation will be discussed in section 5.6.1.2:



GRAPH 5.5 ILLUSTRATION OF WATER TEMPERATURE IN SUPPLY PIPE

The final simulation, where the temperature sensor is placed on the water supply pipe (as illustrated by Figure 5.7 c.) seems to give optimal energy consumption. In closer look into what the reason for that is, a plot of the water temperature and flow rate of the supply pipe and the circulation pipe is made. Graph 5.5 shows the plot of the selected parameters for an hour. For this simulation, the maximum time step of 5s is used. It can be seen that the water temperature in the supply pipe (marked with a blue line on the graph) increases as water is drawn off at the tap (marked with a yellow line on the graph). There is a slight overshoot on the water temperature as it exceeds 50°C. It can be noted that after the tapping is completed the water temperature starts to fall, but does not go under the temperature set point for activating the circulation loop. This results in less frequent circulation in the system and therefore less heat loss. In fact, circulation only occurs in 23% of the time over a year, based on hourly values for flow rate in the circulation pipe. For the remaining 73% of the time water temperatures in the supply pipe are high enough, so after cooling down until the next tapping, circulation is not activated. That phenomenon might be to an extent misrepresented as the simulation uses a single hourly profile, where there is tapping for every hour of the day. In reality, there might be periods of time, especially during night time, without tapping. That will allow the water to cool down enough for the circulation to be activated.

5.6.1.2 SYSTEM PERFORMANCE BASED ON MULTIPLE NODE PIPE COMPONENT

As one of the limitations of the software is to simulate system performance by using a one node model, an attempt to work around that issue is made. That is a point of interest in order to observe how the water temperature changes along pipes with relatively big length. Therefore, the supply and the circulation pipes are split in several shorter pipes, each of which represents a control volume of the pipe and therefore the water inside. The simulations software showed instabilities in simulating the models with several pipe components and for that reason, both the supply pipe and the circulation pipes were split in 5 parts with equal length of 8m each as show in Figure 5.8. With the more detailed representation of the water temperature distribution in the system, the total energy consumption shows to be slightly higher than what was initially simulated, being 16660 kWh/year with heat loss to indoor being 22.5%. Having in mind that the results could be misleading due to the nature of the input as already discussed, the only conclusion that can be drawn is that the detailing of the model has an influence on the expected use.

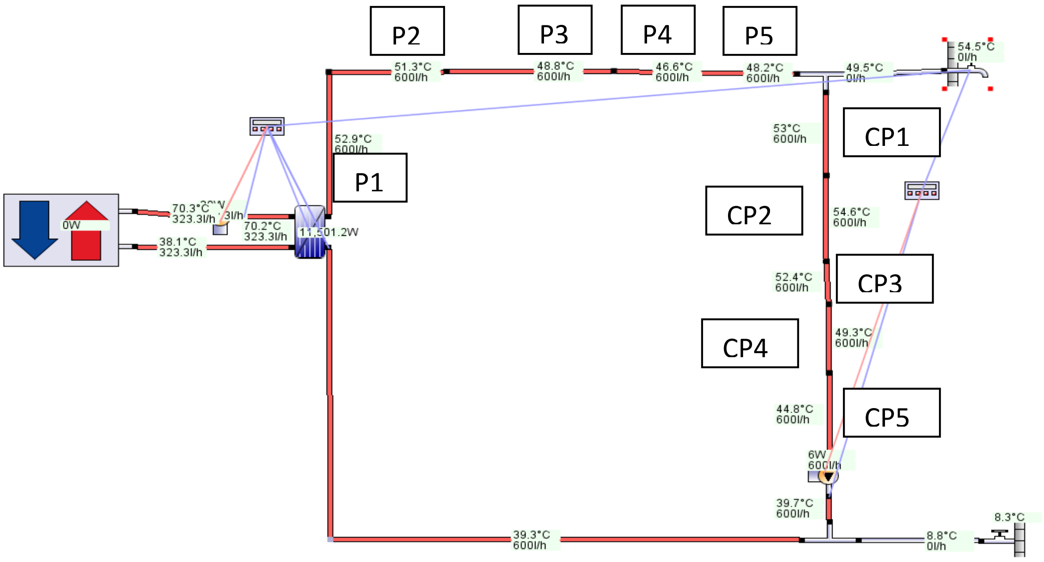


FIGURE 5.8 SCHEMATIC ILLUSTRATION OF THE SPLIT OF PIPES

Figure 5.8 shows an illustration of the system which indicates the splitting of the pipes and the appointed naming. It must be noted that this is only a graphical representation not in scale and is used only for visualizing the system. None of the input parameters are influenced by the graphical representation.

After each tapping, there is a series of circulations in order to maintain the water temperature in the system at the given set point, in this case 38°C. An overshoot on the water temperature is observed in the beginning of tapping, which happens because the circulation loop is activated and then feeds water to the return on the secondary side with temperatures of 38°C and above.

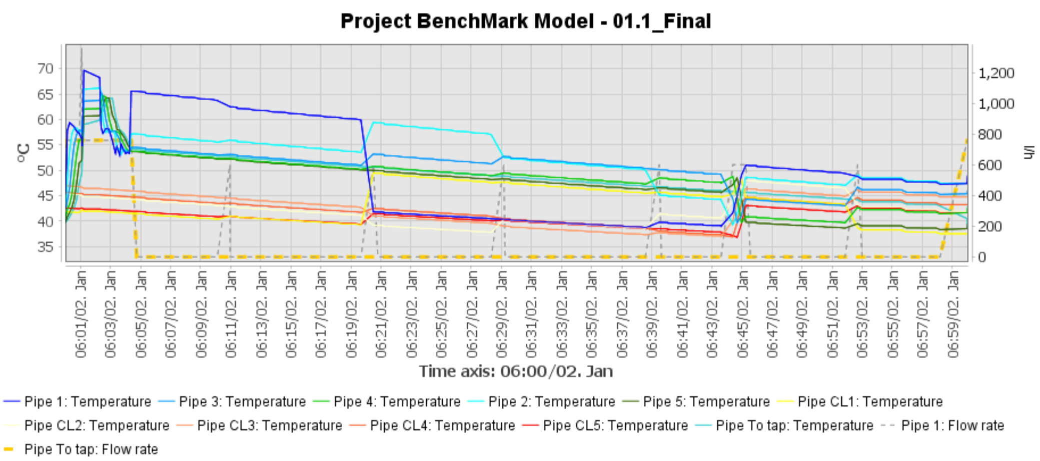


FIGURE 5.9 TEMPERATURE DISTRIBUTION IN PIPES FOR TEMPERATURE SENSOR AFTER CIRCULATION PUMP

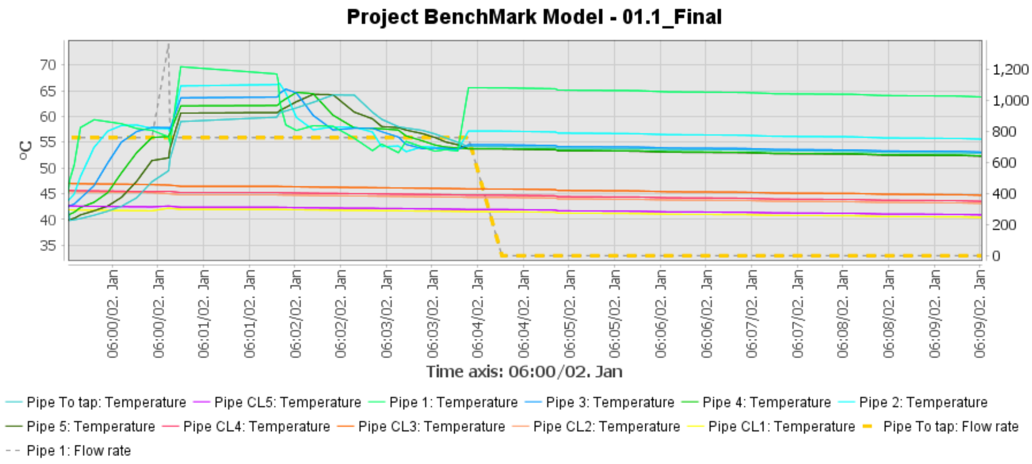


FIGURE 5.10 TEMPERATURE DISTRIBUTION IN PIPES FOR TEMPERATURE SENSOR AFTER CIRCULATION PUMP – 1 HOUR

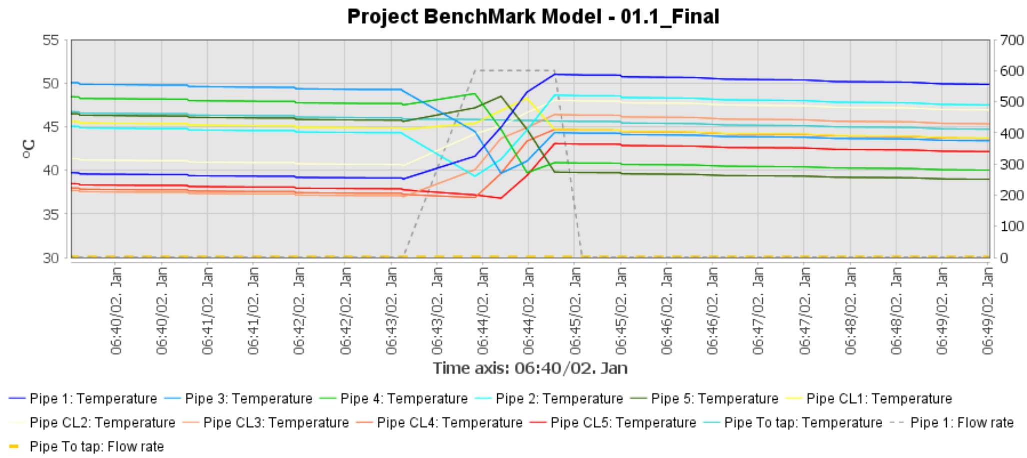


FIGURE 5.11 TEMPERATURE DISTRIBUTION IN PIPES FOR TEMPERATURE SENSOR AFTER CIRCULATION PUMP – DURING CIRCULATION

Another overshoot is observed during circulation cycles, which can be seen on Figure 5.11. That is to be expected, since the temperature sensor is placed on the end of the circulation loop.

5.6.1.3 SENSOR PLACEMENT BEFORE CIRCULATION LOOP

The new placement of the temperature sensor for activating the circulation loop is on pipe 5 (P5) on Figure 5.8. Placing the sensor on just before the connection with the circulation can contribute to significant reduction of the energy use and more stable and consistent temperature distribution. The resulting energy use is 13690 kWh of which the heat loss is 16.6%. The total energy use is reduced by 18% compared to the first simulation.

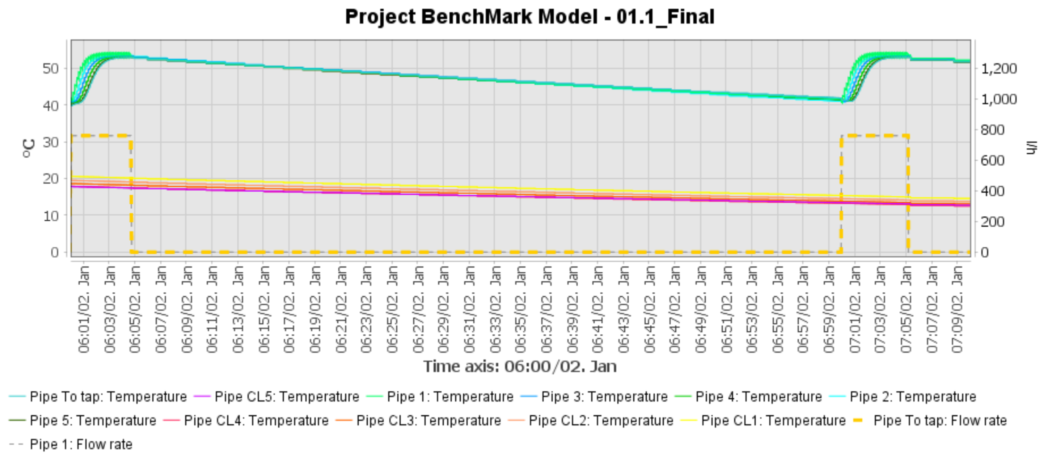


FIGURE 5.12 TEMPERATURE DISTRIBUTION IN PIPES FOR TEMPERATURE SENSOR BEFORE CIRCULATION LOOP

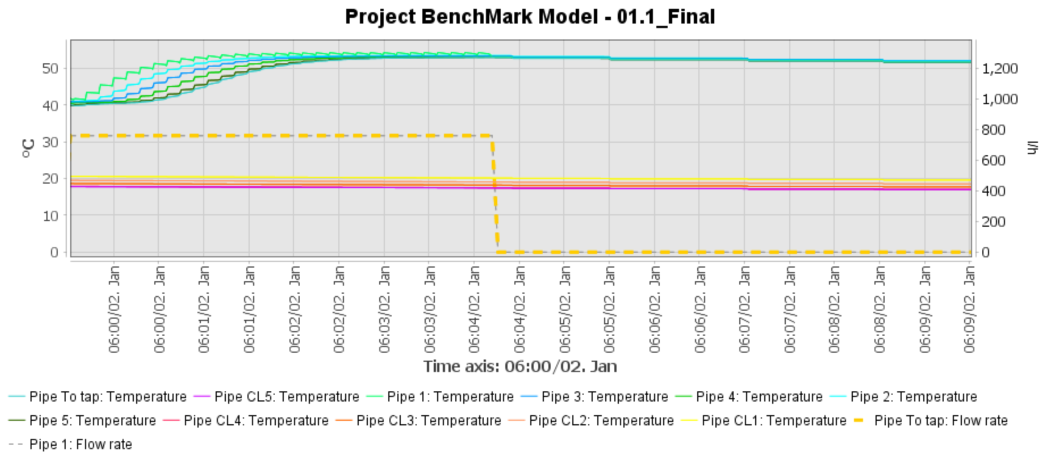


FIGURE 5.13 TEMPERATURE DISTRIBUTION IN PIPES FOR TEMPERATURE SENSOR BEFORE CIRCULATION LOOP – DURING TAPPING

By placing the sensor before the circulation loop, the temperature distribution is much more stable. Circulation does not seem to be activated since the water temperature on P5 is sufficiently high. As the whole pipe is filled with hot water, the cool off time is long, which prevents the circulation from activating. The large amount of water per draw off is due to the fact that the water demand for 10 apartments is put on a single tap, due to the nature of the simulation software. In reality, draw-offs could be of much smaller volumes and occur more rarely than what the setup of the model represents. To further investigate the issue, a more detailed look into possibly a single day of use need to be taken.

5.6.1.4 SIMULATION WITH LOAD FOR ONE APARTMENT

When using the same model setup as previously for the benchmark system, applied to a single user, the simulation shows that the energy demand is not met. That is a result of the small volumes of water that are drawn off when tapping. The water in the system is maintained at a temperature of 38°C and above. However, tapping from only one consumer is not enough to displace the contained in the pipe water with high temperature water. As a result of that, the water that reaches the tap is with a temperature of around 38°C and thus the hot water demand is not met.

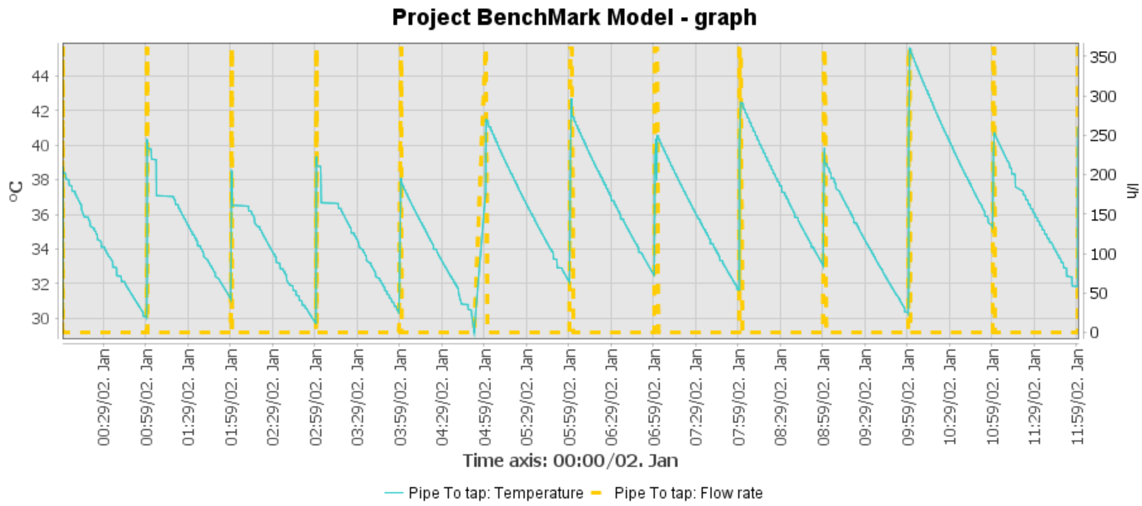


FIGURE 5.14 TEMPERATURE DISTRIBUTION IN PIPE BEFORE TAP FOR CIRCULATION SETPOINT 38°C – DELIVERED TEMPERATURE WHEN TAPPING

For the purpose of the analysis, the temperature set point for activating the circulation loop is increased, so it meets the energy demand of the system. That is at a temperature set point of 45°C, with temperature sensor on the pipe before the connection with the circulation loop (P5 on Figure 5.8)

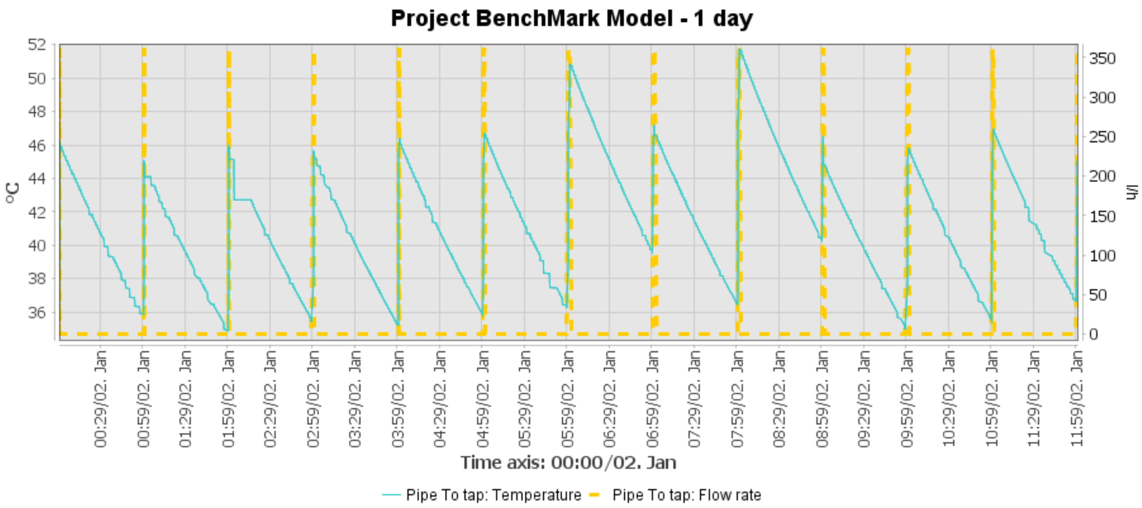
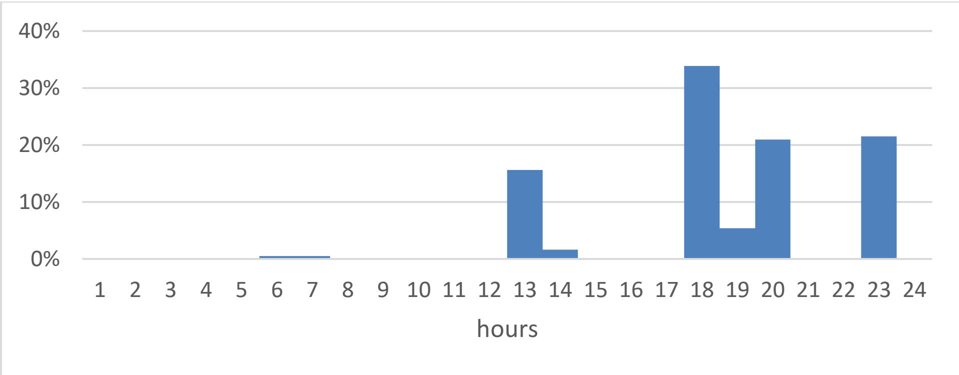


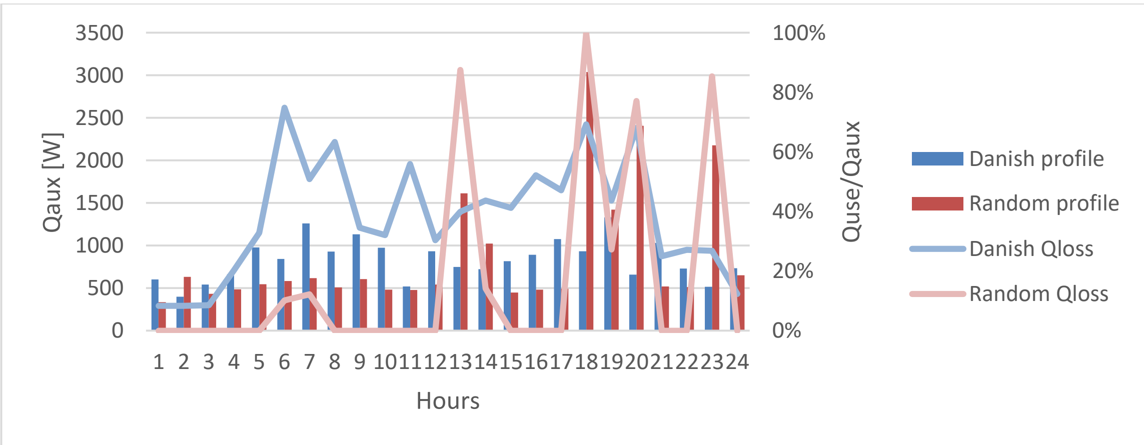
FIGURE 5.15 TEMPERATURE DISTRIBUTION IN PIPE BEFORE TAP FOR CIRCULATION SETPOINT 45°C – DELIVERED TEMPERATURE WHEN TAPPING

With this setup the simulation software shows that the energy demand is met. Using this setpiont, a closer look into how the system uses and distributes energy is taken. The total yearly consumption is disregarded as it is considered that it does not represent the real consumption of such system. The simulation is used to establish a base for comparison between system performance using a standard hourly profile, described in detail previously, and suggestion for a specific hourly profile based on a data from another similar residential building in Denmark. For the purpose of the comparison, only the performance over a single day is presented. As discussed previously the standard profile is developed based on data from several households over a period of time. That results in a profile, where there is water consumption for each hour of the day. The alternative profile used in this comparison represents a single day, picked randomly from a data set.



GRAPH 5.6 HOURLY PROFILE OF A RANDOM DAY FROM A RESIDENTIAL BUILDING IN DENMARK

It is apparent that there are only certain hours where there is water consumption. Expectedly, there are hours, especially during the night time, where there is no consumption. The DHW systems are evaluated based on the produced energy from the energy source compared to the utilized energy from the user.



GRAPH 5.7 PRODUCED AND UTILIZED ENERGY FOR DHW – COMPARISON BETWEEN USE FOR 24 OF TWO CASES

The system using the standard profile utilizes on average 38% of the produced energy for this particular day, while the alternative profile only 17%. However, due to the fact that the used volume is concentrated in a few periods, the alternative profile shows better utilization of energy at draw-off. It cannot be concluded how the system performs overall, since the use of water is highly irregular both in terms of time, duration and volume. The alternative profile cannot be applied, as it is not representative for an entire user group. It can neither be applied to a multistory building where the likelihood of several apartment using or not using water at the same time is small. However, relatively long periods in a day of no water use can occur. As a result of that, the comparison indicates the inefficiency due to circulation.

A solution to the issue of heat losses associated with recirculation of hot water is to turn off the circulation pump when not needed. There are circulation pump products on the market, which are self-programmable to learn the usage pattern of hot water in a building. They operate on the base of a running log of measurements, that way being able to adapt. However, these types of products might not be suitable for every application. Multistory buildings might require a more advanced control system if such solution is to be implemented.

Summarizing the results from the investigation, it can be said that the placement of the temperature sensor for activation of the circulation can cause circulation during tapping if not properly placed on the circulation loop. This can be avoided by placing the sensor on the supply pipe before the circulation loop. In this case however, the set point for the activation of the circulation might require to be increased in order to ensure sufficient water temperature reaching the taps. The activation of the circulation, the placement and the sensor and delivering water with sufficient temperature to taps is dependent on the contained volume of water in the system and the frequency of water draw-offs. The more water with high temperature there is as a result of increased use, the less circulation is required and water in the systems could be maintained at a higher temperature and volume.

5.6.1.5 VARIATION OF CIRCULATION LOOP LENGTH

For the benchmark model it is assumed that the connection of the vertical supply pipe and the circulation loop pipe is immediately before the tap. Thus, water in circulation is kept close to the tap and at tapping only the water in the pipe to the tap must be displaced before hot water reaches the tap. That requires a short amount of time.

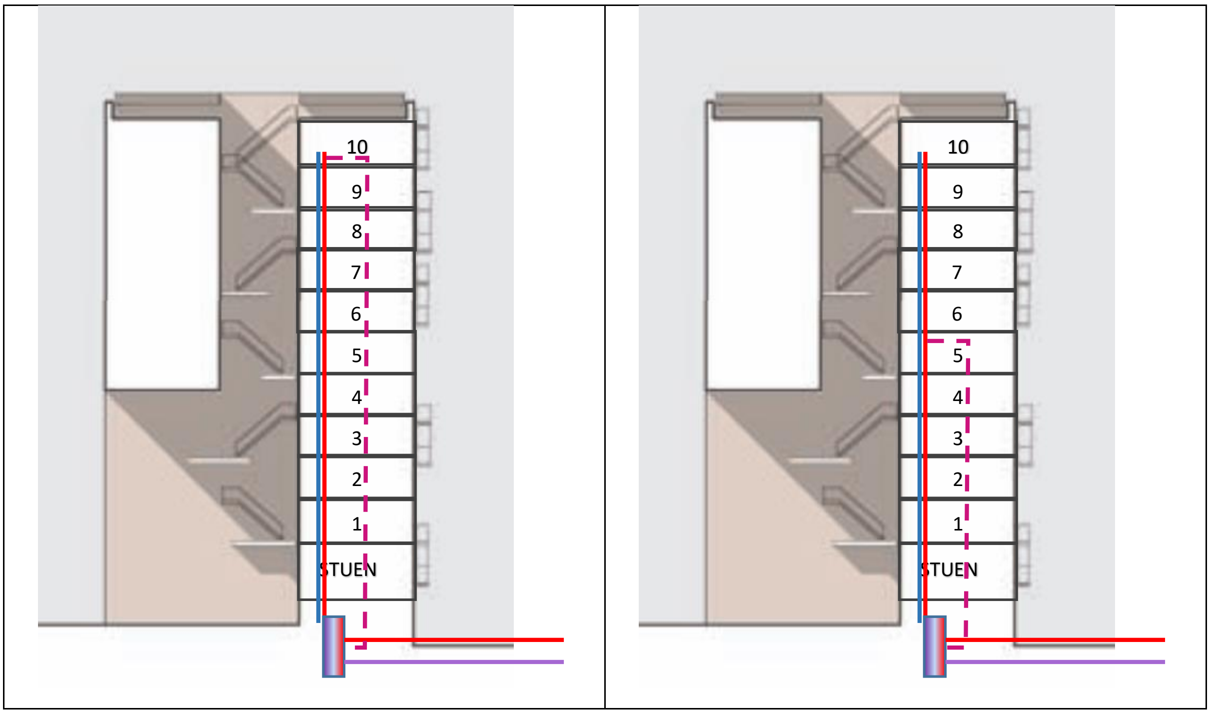


FIGURE 5.16 ILLUSTRATION OF VARIATION IN THE CONNECTION POINT OF THE CIRCULATION WITH THE SUPPLY PIPE

In some instances, the circulation can be connected lower on the supply pipe and still fulfil the required waiting time for the hot water to reach the tap. By shortening the circulation loop, the volume of contained water is reduced and consequently, the amount of heat loss from circulation. With this set of simulations, the aim is to find an optimal connection point of the circulation with the supply pipe, for which the energy demand on the tap is still met and the waiting time is lower than 10 s.

As discussed previously, the PolySun model uses a single tapping component for the simulations. Therefore, the connection point of the circulation pipe is always before the tap component in the model and the total water demand is always drawn from the one tap. In reality, however, there are several taps for a system providing water to multiple apartments and the connection point of the circulation can be between taps. That also means that only the amount of water drawn from taps after the connection point is taken into account for calculating the waiting time. Therefore, if there is a smaller number of taps after the connection point that might result in larger volumes of drawn off water for short tapping. As an example, a tapping that is only 0.5 l at a temperature of 50°C, the whole volume of water contained in the remaining of the pipe needs to be displaced, thus increasing the actual tapping volume.

By calculating the contained volume of water in the pipe for a pipe length of 40m and pipe size ¾" with inner diameter 22mm and water flow of 0.2 l/s when tapping, the time for displacing the whole volume is calculated. For the whole amount of water to be displaced, it is required over 78 sec.

$$A_{pipe} = \pi r^2$$

$$V_{pipe} = A_{pipe} * L_{pipe}$$

$$t_{tap} = \frac{V_{pipe}}{\mathrm{q}}$$

Where:

A_{pipe} [m²] is the inside area of the pipe

r [m] is radius to the internal surface of the pipe

V_{pipe} [m³] is the volume of the pipe

L_{pipe} [m] is the length of the pipe

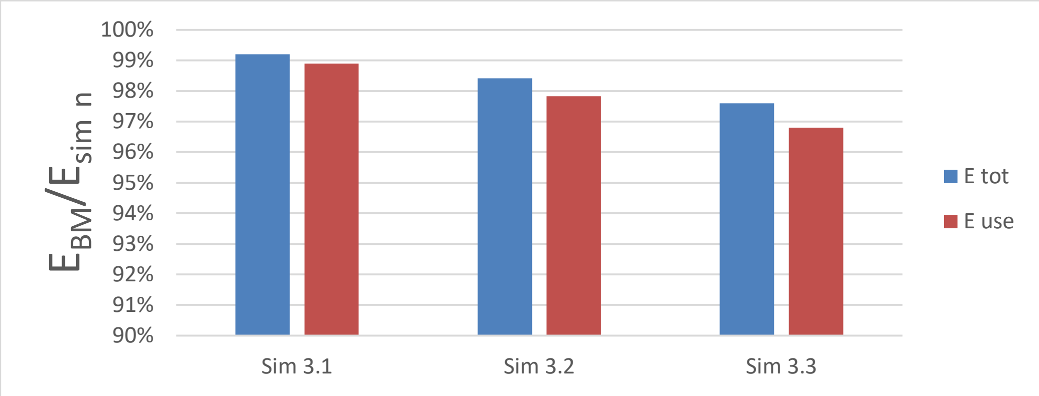
t_{tap} [s] is the duration of taping for the contained volume to be displaced

q [l/s] is the volumetric flow in the pipe

EQUATION 5.4 VOLUME OF CONTAINED WATER IN A PIPE

Using the same approach, it can be calculated the maximum pipe length, where the contained water is displaced for 10 sec. That results in a little over 5m of ¾” pipe. That gives an indication of the connection point of the circulation pipe with the supply pipe. This calculation is only used as a guideline, as in reality not the whole volume of water in the pipe needs to be displaced because at times the contained water in the remaining pipe could be with a sufficiently high temperature.

The latter indication is confirmed by the simulation model developed for this case. The total length of the circulation system is made of the supply pipe and the circulation pipe. It is varied in three steps, where the length of the supply pipe and the circulation pipe are kept equal. For the BM setup, a total length of 80m is used, as 40m for each pipe is assumed to be realistic length to cover the distance between the technical room and the furthest tap 10 floors high in the building. For the three variations, a reduction on the length is made of 5m for each variation. That is respectively a length of 75m, 70m, and 65m, for the three variations. A variation with a total pipe length of 60m was made, although the result from the simulation software showed that the energy demand is not met, which is an indication of too low water temperature at the tap.

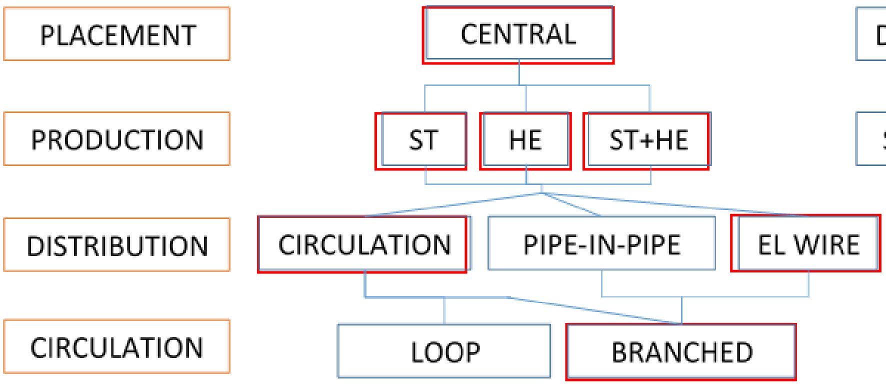


GRAPH 5.8 RELATIVE COMPARISON BETWEEN ENERGY USE FOR THREE SETUPS WITH DIFFERENT CIRCULATION LOOP LENGTH

As shown on Graph 5.8, the shorter circulation length results in smaller total energy use in the system. The results are represented by the relative energy reduction compared to the BM model.

6 OTHER COMMONLY USED TYPES OF DHW SYSTEMS

There are many types of DHW systems available for use today. The DHW system has the function 55°C, and then reach the taps of the system. The design of the system is dependent on many factors, among which functionality, local codes and regulations, energy supplier conditions for use, economy, etc. In an attempt to systematically group the most common DHW systems, the Danish Building Research institute have come up with an illustration in their report (1), describing the systems and their components.



A diagram for DHW system with regards to hot water production and distribution

ST – storage tank

HE – heat exchanger

ST+HE – combination of a storage tank and a heat exchanger

CIRCULATION – a pipe system, where water is returned to the energy producing component via a pump

PIPE-IN-PIPE – a pipe system where an outer tube supplies the hot water and the inner tube returns water to the energy producing component

EL WIRE – a system where the pipe is wrapped in an electrical wire, which via electricity heats the water in the pipe

LOOP – a piping system which is led through the building in a loop, providing water to all taps, where the last part of the pipe is used for circulation

BRANCHED – a piping system, where there is one main pipe, which is branched off to several secondary supply pipes, which reach taps in different sections of the building

The focus in this report is on comparing central systems with either external heat exchanger or hot water tank, with circulation or el-tracing.

Previously in the report, a DHW system with external heat exchanger and circulation loop was discussed in the context of the developed case study. The goal for this chapter is to compare the feasibility and efficiency of that system with other commonly used systems.

6.1 STORAGE TANK SYSTEM

One of the DHW systems often used in buildings is a system with a hot water storage tank. That type of systems enables to shift energy load in time, as the storage tank serves as a buffer. Thus allowing for lower peak power requirement from the energy source. The system however requires more space for installation of the tank.

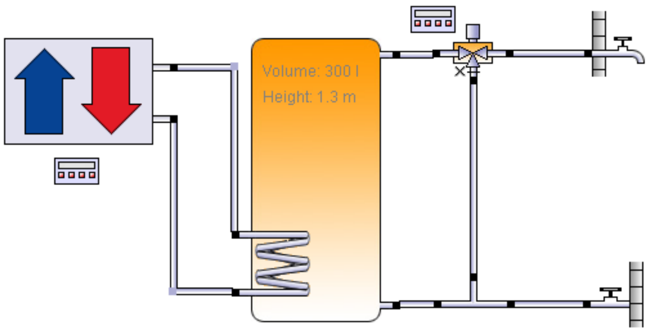


FIGURE 6.1ILLUSTRATION OF A TYPICAL DHW SYSTEM WITH A STORAGE TANK

There are several setups of a storage tank water system. Depending on whether the water in the tank should be drinkable or not the system could be with an internal or external heat exchanger, with reference to the tank. Both types have the effect of storing energy in the water in the tank. The system used in this assessment and comparison is with a storage tank with internal heat exchanger as that minimizes heat loses and inefficiencies that occur in external heat exchangers.

6.2 DHW SYSTEM WITH EL-TRACING

Although the design of DHW system with water circulation loop one of the most common solutions for multistorey buildings, it is certainly not the most efficient solution. An alternative for the circulation loop is an el-tracing wire around the supply pipe to the users, which maintains the required temperature in the pipe by providing heat directly to the pipe and the water running through it. In some instances this solution could be more effective as it eliminates the need for the circulation loop and therefore shortens the pipe lengths and reduces the volume of contained water within the pipe, resulting in smaller loss. It also eliminates the need for pumping water through the circulation loop and the energy required for it.

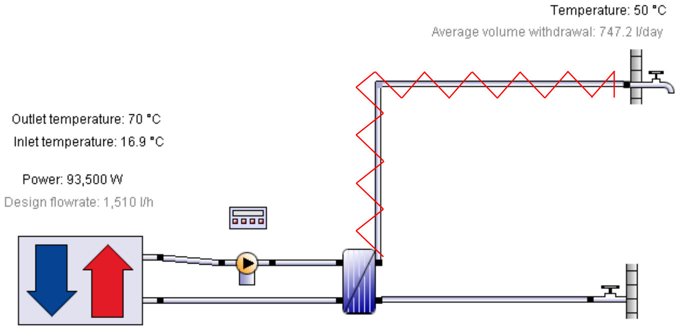


FIGURE 6.2 DHW SYSTEM WITH AUXILIARY PREHEATING OF WATER BY AN ELECTRICAL WIRE (EL-TRACING)

For larger systems with bigger length of pipes and large contained water volumes this might not be the most efficient solution. However, for smaller, less lengthy installations, this solution could be beneficial.

7 COMPARISON BETWEEN SYSTEMS

This chapter presents some comparison between the system used for the case study building and some alternative systems, mentioned previously in the report.

7.1 DHW SYSTEM WITH A STORAGE TANK

Another model for a DHW system is developed with a storage tank based on the reference building used in the previous simulations. As such, the model uses the same input data in terms of hot water demand and user profile.

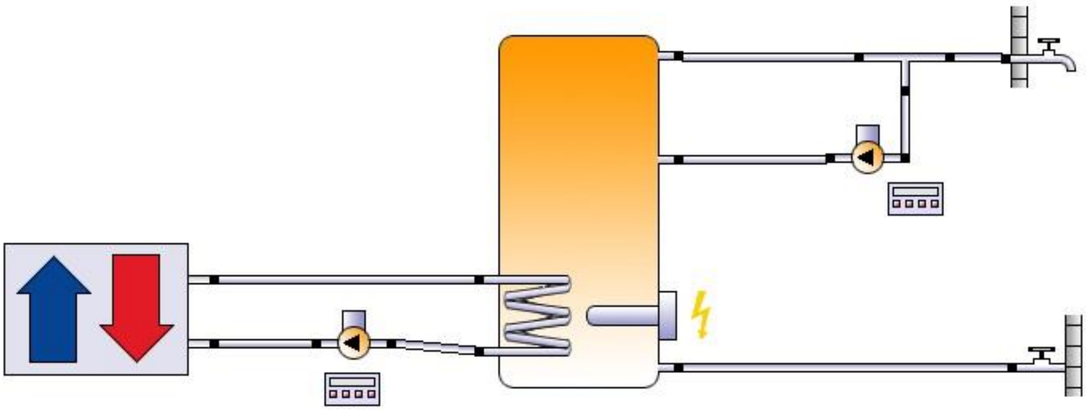
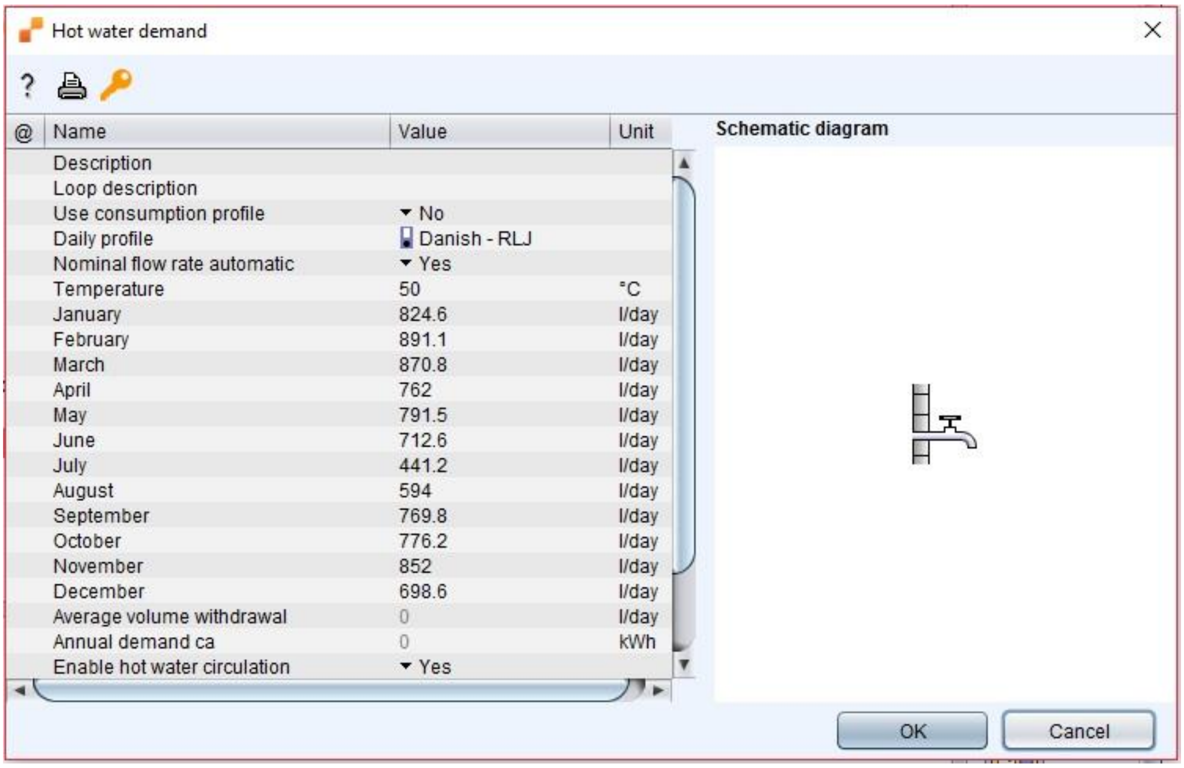


FIGURE 7.1 INITIAL DESIGN OF THE STORAGE TANK SYSTEM



Hot water demand

@	Name	Value	Unit
	Description		
	Loop description		
	Use consumption profile	No	
	Daily profile	Danish - RLJ	
	Nominal flow rate automatic	Yes	
	Temperature	50	°C
	January	824.6	l/day
	February	891.1	l/day
	March	870.8	l/day
	April	762	l/day
	May	791.5	l/day
	June	712.6	l/day
	July	441.2	l/day
	August	594	l/day
	September	769.8	l/day
	October	776.2	l/day
	November	852	l/day
	December	698.6	l/day
	Average volume withdrawal	0	l/day
	Annual demand ca	0	kWh
	Enable hot water circulation	Yes	

Schematic diagram

OK Cancel

FIGURE 7.2 USER PROFILES FOR HOT WATER DEMAND

Storage room where the tank should be located is defined with a mean temperature. For this model, this temperature is chosen as indoor temperature of 20°C; this will later be used for the heat loss calculation. The energy source is District heating, and hot water is run through the built-in heat exchanger to heat up the water inside the storage tank. The system once again includes a circulation system which flow rate is controlled by a pump.

The storage tank is chosen from the Polysun database, based on its capacity of 900L to cover the DHW consumption for the reference building. The tank should be able to maintain an operational temperature of at least 60°C in order to avoid the risk of running Legionella bacteria growth, as mentioned section **Error! Reference source not found.**.

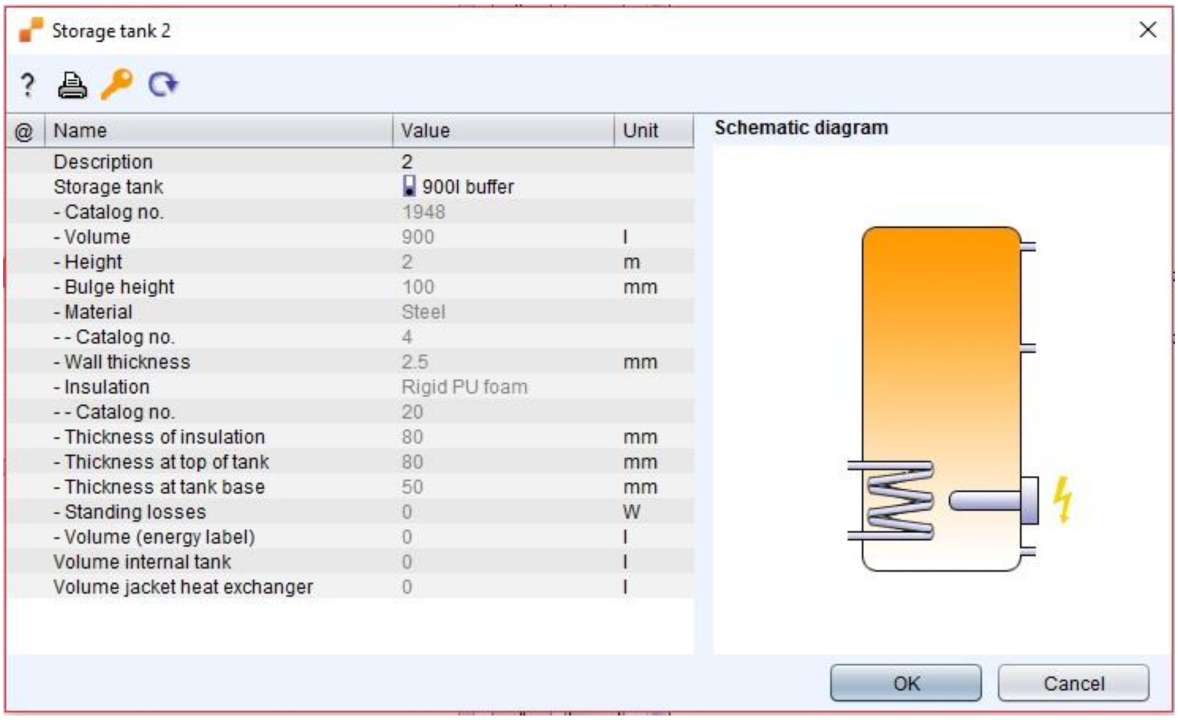


FIGURE 7.3 STORAGE TANK SPECIFICATION

Heat losses from the storage tank should be calculated for the cylindrical shell and for the top/bottom plate. In order to calculate the cylindrical shell heat transfer, the following equation is used:

$$V = \pi r^2 h$$

Where:

V [m$^{3]}$ is the volume of the storage tank

H [m] is the height of the storage tank

R [m] is the radius of the water tank

EQUATION 7.1 CYLINDRICAL VOLUME

The volume of the tank is 900l, the height is given as 2m, therefore $900/1000=2\pi r^2$ gives the r=0.37. The heat transfer is the calculated using:

$$Q = \frac{2\pi L(T_i - T_e)}{\frac{\ln\left(\frac{r_e}{r_i}\right)}{k} + \frac{1}{r_e h}}$$

Where:

R_i [m] is the radius to the internal surface

R_e [m] is the radius to the external surface

L [m] is the height of the storage tank

T_i [C°] is the internal tank temperature

T_e [C°] is the mean indoor temperature

H [W/m^2C°] is the convective heat transfer coefficient at an indoor temperature of 20°C

K [W/mC°] is the thermal conductivity (calculated from polysun)

EQUATION 7.2 TOTAL HEAT TRANSFER THROUGH THE CYLINDRICAL SHELL

$$Qshell = \frac{2\pi 2(60-40)}{\frac{\ln\left(\frac{0.45}{0.37}\right)}{0.03} + \frac{1}{1.35}}$$

EQUATION 7.3 TOTAL HEAT TRANSFER THROUGH THE CYLINDRICAL SHELL

The heat transfer of the cylindrical shell is 72.29 W.

For the heat transfer from the top surface of the tank, the following equation is used:

$$Qtop = \frac{T_i - T_e}{\frac{1}{hA} + \frac{\Delta x}{kA}}$$

Where:

T_i [C°] is the internal tank temperature

T_e [C°] is the mean indoor temperature

H [W/m^2C°] is the convective heat transfer coefficient at an indoor temperature of 20°C

K [W/mC°] is the thermal conductivity (calculated from polysun)

A [m^2] is the area of the plate

Δx [m] is the thickness at the top of the tank

EQUATION 7.4 HEAT TRANSFER FROM THE TOP OF THE TANK

$$Qtop = \frac{40}{\frac{1}{3(\frac{0.9}{2})} + \frac{0.09}{0.03(\frac{0.9}{2})}}$$

The heat transfer from the top plate is 5.4 W.

For the bottom plate, it is defined as:

$$Qbottom = -kA(T_e - T_i)/\Delta x$$

Where:

T_i [C°] is the internal tank temperature

T_e [C°] is the mean floor temperature (temperature outside of the tank in the storage space)

Δx [m] is the thickness at the bottom of the tank

A [m^2] is the area of the plate

EQUATION 7.5 HEAT TRANSFER FROM CONDUCTION THROUGH THE BOTTOM OF THE TANK

$$Qbottom = -0.03 \times 0.45(-50)/0.12$$

The heat transfer from the bottom plate is 5.6 W.

The total heat transfer of the storage tank is defined as:

$$Qtank = 72.29\text{W} + 5.4\text{W} + 5.6\text{W} = 83.29\ \text{W}$$

7.1.1 VARIATION IN PLACEMENT OF TEMPERATURE SENSORS

A number of simulations are performed with the storage tank model where the placement of the temperature sensor for the water circulation control is changed. As with the benchmark system with a heat exchanger, a comparison of the total energy use and heat loss is made as a result of the different placemen of the temperature sensor on the system., The temperature sensor is placed for the different cases after and before the circulation pump, as well as on the vertical branch following the storage tank. The three different cases are illustrated on Figure 7.4 Placement of Temperature Sensor for Storage Tank system in three different cases:

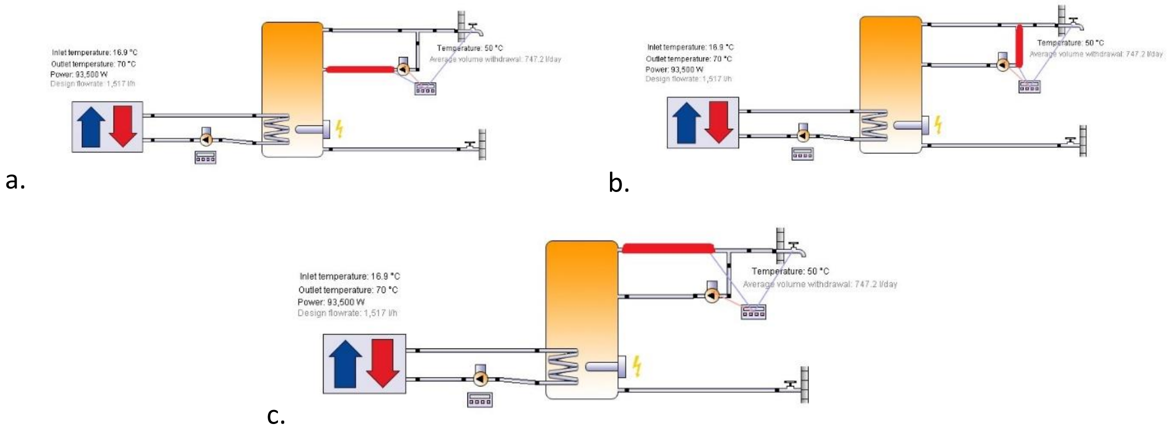
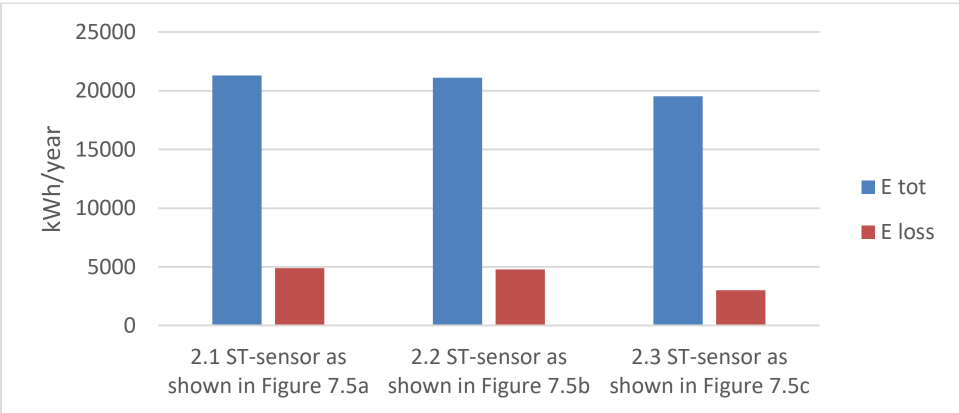


FIGURE 7.4 PLACEMENT OF TEMPERATURE SENSOR FOR STORAGE TANK SYSTEM IN THREE DIFFERENT CASES

The boundary conditions for the storage tank system variations remains the same as the one used for the benchmark system with a heat exchanger. Therefore, DHW consumption values and monthly factors, as well as user profile are all used as input for the three models. The system components that both systems share are also identical. The source remains DH with design values for 70°C supply and 40°C return water temperatures.

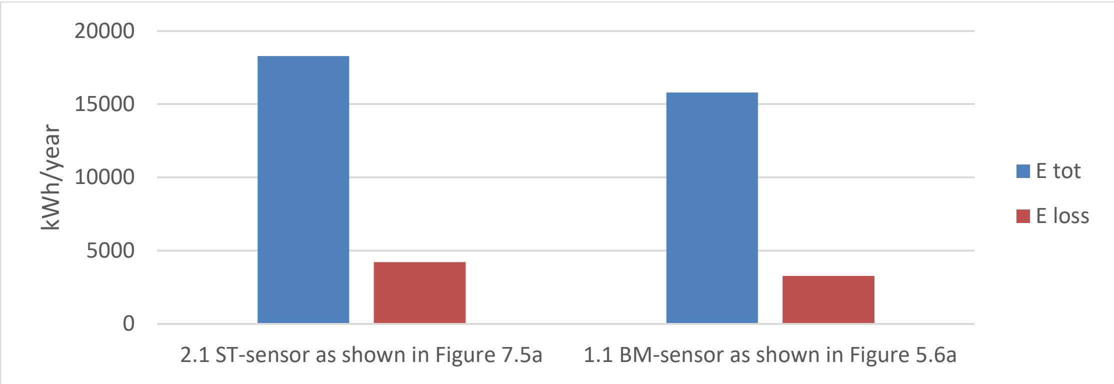
The energy use in comparison of the three different cases of storage tank sensor placement is illustrated on Graph 7.1:



GRAPH 7.1 COMPARISSON BETWEEN ENERGY CONSUMPTION FOR THREE CASES

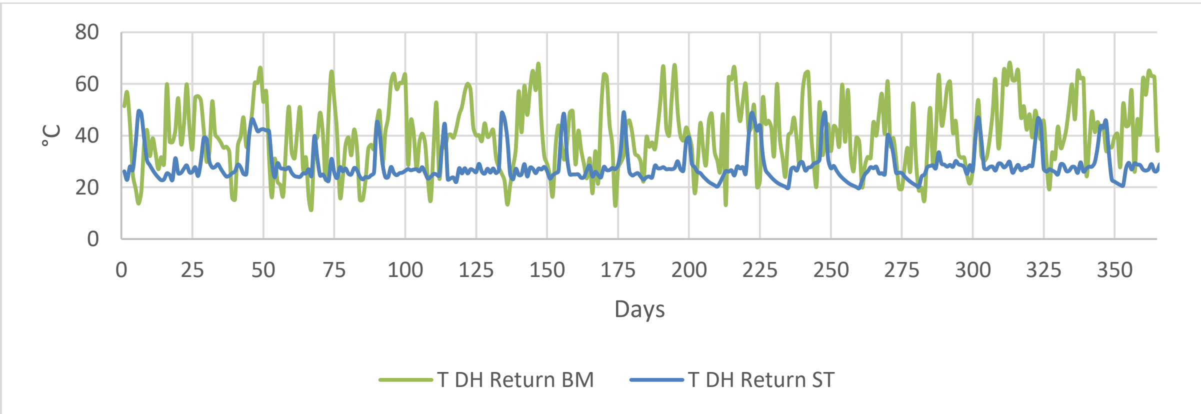
The results once again show a reduced total system energy use, with an 8% reduction between cases 2.1 to 2.3. In addition, the total heat losses from the pipes are reduced by 8% from 23% on case 2.1 to 15% to case 2.3. This observation once again implies that the placement of the temperature sensor has a certain impact on the system energy use, as the tendency first noted in the benchmark system simulation also applies for a storage tank system.

A comparison between the total energy use of this system and the benchmark system established earlier in this report shows that the storage tank system has a 14% higher energy use that the system with a heat exchanger unit. Both systems are compared in their default setup with the temperature sensor placed after the circulation pump. The higher energy consumption is possibly due to the larger overall volume of hot water within the system as a result of the storage tank. Since the temperature of the water inside the tank should be constantly maintained at 60°C, the additional energy spent for that purpose affects the total energy consumption of the system.



GRAPH 7.2 COMPARISON BETWEEN BENCHMARK SYSTEM AND STORAGE TANK SYSTEM

However, when looking at the temperature variation of the return DH water between both systems on an hourly basis, it can be seen that the return water temperature from the storage tank system is consistently lower throughout the year when compared to the one in the benchmark system, and even though it also reaches temperatures higher than the design value of 40°C for return DH water, the overall fluctuation is not as stark.



GRAPH 7.3 TEMPERATURE VARIATION IN DH RETURN WATER IN BM AND ST SYSTEMS

When looking at the total number of hours per year for which the return temperature is above 40°C, it is notable that the storage tank system is able to return the DH water at lower temperatures than the design value for a bigger number of hours per year than the system with a heat exchanger. The total number of hours for which the return temperatures exceeds 40°C in the storage tank is 2191, which is 28% lower than the value for the benchmark system, and in turn translates in a total 10% reduction from the total number of operational hours for which both systems are being simulated.

SYS	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	**TOT**
BM	316	254	259	237	202	193	254	205	213	261	292	360	**3046**
ST	73	96	117	123	140	149	237	184	203	251	280	338	**2191**

TABLE 7.1 NUMBER OF HOURS WHERE DH RETURN TEMPERATURE IS HIGHER THAN 40°C

The lower return temperatures in the storage tank system could indicate that this particular system is able to promote a higher heat transfer between the DH medium and the hot water produced in the storage tank for these boundary conditions and this specific hot water demand, thus being able to extract more energy from the DH exchange. Proper heat stratification in the water in the storage tank allows the water temperature on the bottom to be low enough in order to promote efficient heat transfer and cooling on the heat source, while water on the top being with high enough temperature to provide required power output to taps. In systems with circulation such flexibility is more difficult to be achieve due to the relatively low temperature on the circulation and smaller overall volume of the system.

The issue of higher return temperatures in DHW systems nowadays is very common in many buildings, both new and renovated, and a possible further research topic could investigate the impact of high return temperatures and how it can be optimized in both types of systems, as well as the financial benefits for the consumers of DHW.

7.2 DHW SYSTEM WITH ELECTRICAL WIRE (EL-TRACING)

For the purpose of the comparison between the benchmark systems and alternative systems, an attempt to model DHW system with el-tracing is made. However, the simulation tool does not contain a component that can represent the auxiliary el tracing heat source and therefore is unable to perform such simulation. Instead, a mathematical model is developed, using the same input as the one in the simulations. The heat losses from the supply pipe to the tap and the circulation pipe are calculated. The model is used to calculate only the heat losses through the pipe for the occasions when the water is standing still in the pipes. Water is moving for a very short periods of time upon water draw-offs, in addition to what is assumed to be small heat loss when water is moving in the pipe, resulting in small energy losses. It is assumed that the heat loss from the pipes must be covered by the electrical wire in order to maintain constant temperature of 50°C at all times. When using electrical power and a wire for heating it can be assumed that the power output from the wire is instantaneous and 100% of the electrical power is converted to heat.

As discussed previously, the simulation tool calculates the results for a system based on a single continuous water draw-off in the beginning of each hour, which lasts until the specified water demand is reached under a predefined water flow. That might not be an accurate representation of the real life timing of each water draw off, however in terms of heat loss and energy use such a simplification does not have a significant effect on the results. For the calculation model for the DHW system with electrical wire, the same principle is used to calculate the time for which the water stands still in the pipes and therefore the demand for provided auxiliary energy.

7.2.1 HEAT TRANSFER

Heat transfer for cylinders is similar to heat transfer for shapes with flat surfaces, with the exception that the surface area of cylinders' wall increases, as the heat flows from inside to outside.

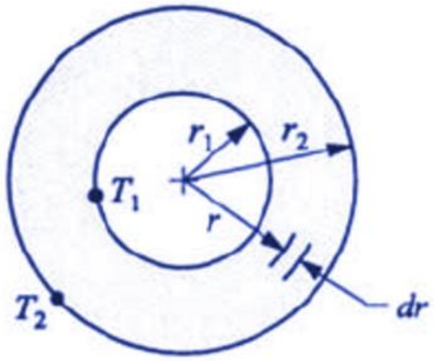


Image ref.: www.engineersedge.com(12)

$$\dot{Q} = -k * A * \left(\frac{\Delta T}{\Delta r}\right) \text{ [W]}$$

$$A_{lm} = \frac{A_{outer} - A_{inner}}{\ln\left(\frac{A_{outer}}{A_{inner}}\right)} \text{ [m}^2\text{]}$$

$$A_{lm} = 2\pi L\left(\frac{r_{outer} - r_{inner}}{\ln\left(\frac{r_{outer}}{r_{inner}}\right)}\right) \text{ [m}^2\text{]}$$

$$\dot{Q} = 2\pi kL\left(\frac{T_o - T_i}{\ln\left(\frac{r_o}{r_i}\right)}\right) \text{ [W]}$$

Where:

Q [W] heat loss

k [W/m^2.K, W/m^2.°C] heat transfer coefficient

A [m^2] area

ΔT [K,°C] temperature difference between two phisical systems

Δr [m] difference between the external and internal radius of a cylinder

A_{lm} [m^2] logaritmic mean area (of a cylinder)

L [m] length (of a cylinder)

r_{inner} [m] radius to the inner surface of a cylinder wall

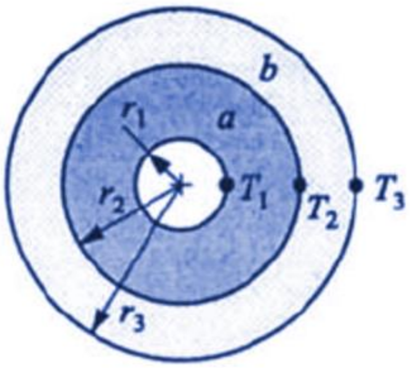
r_{outer} [m] radius to the outer surface of a cylinder wall

T_i [K,°C] temperatire of fluid in the cylinder

T_o [K,°C] ambient temperature

FIGURE 7.5 FOURIER'S LAW APPLIED FOR CYLINDERS

Therefore, the log mean area of the wall is used for calculating the heat transfer. The same is valid for both single layer cylinders and cylinders with multiple layers. In the case of an insulated pipe, heat flows through two layer cylinder wall.



$$Q = \frac{2\pi L(T_o - T_i)}{\frac{\ln\left(\frac{r_2}{r_1}\right)}{k_{steel}} + \frac{\ln\left(\frac{r_3}{r_2}\right)}{k_{insu}} + \frac{1}{h_0 r_3}}$$

Image ref.: www.engineersedge.com(12)

Where:

L [m] is pipe length

$\boldsymbol{T_o}$ [C°] is ambient temperature

$\boldsymbol{T_i}$ [C°] is water temperature

$\boldsymbol{r_1}$ [m] is radius to the internal surface of the pipe

$\boldsymbol{r_2}$ [m] is radius to the external surface of the pipe

$\boldsymbol{r_3}$ [m] is radius to the external surface of the insulation

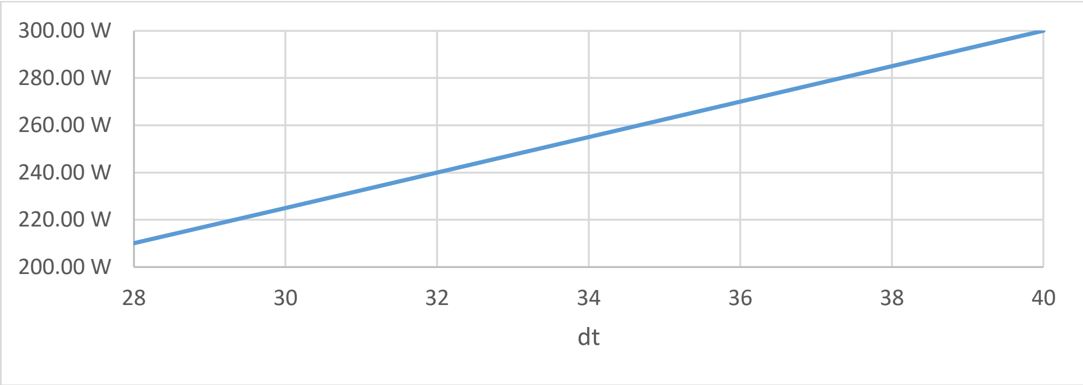
$\boldsymbol{k_{steel}}$ [W/mC°] is thermal conductivity of steel

$\boldsymbol{k_{insu}}$ [W/mC°] is thermal conductivity of insulation

$\boldsymbol{h_0}$ [W/m^{2}C°] is external convective heat transfer coefficient (calculated at R_0=0.04, for horizontal heat transfer)

FIGURE 7.6 FOURIER'S LAW APPLIED FOR INSULATED CYLINDER

The heat loss from the pipes is based on a ¾" stainless steel pipe with thermal conductivity value λ = 16 W/mK with 30 mm insulation with thermal conductivity value λ = 0.036 W/mK and total length of the water supply pipe being 40 m. Water temperature in the pipe is taken at 50°C or the calculated average temperature in the pipe and the ambient temperature at 10°C. Using the method described in Appendix C and cross-referenced with diagrams from EngineeringToolbox.com(12), the heat loss form the pipe is 7.5 -8.5 W/m and total of 300 - 340 W for the whole system for temperature difference of 40°C. However, the heat losses for various temperature differences are taken from the illustrated linear dependency between the two, shown by Graph 7.4:



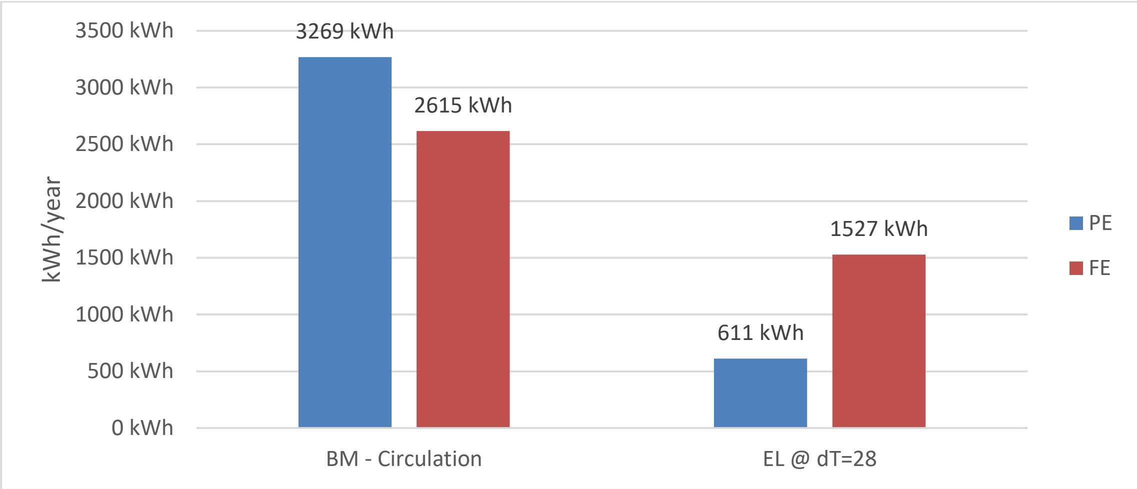
GRAPH 7.4 LINEAR DEPENDENCY BETWEEN HEAT LOSS AND TEMPERATURE DIFFERENCE

For the full calculation refer also to Appendix E .

7.2.2 ENERGY USE

A calculation is made for a temperature difference of 28°C, for water temperature in the pipe of 38°C. Often 38°C is referred to as the usable water temperature at taps after mixing and therefore water systems with circulation loops are often dimensioned for minimum water temperature on the circulation loop of 38°C(13). In this case, 38°C is the design temperature assumed to be maintained in the pipe, since the value is commonly used when designing DHW systems with circulation. Therefore, the energy calculations are based on the heat losses occurring only when the temperature in the pipe is at 38°C. Generally speaking, there is a certain amount of time after every tapping, where the pipes are filled with water with temperatures of around 50°C, then the water cools down to 38°C before any additional heat is applied to maintain it at the desired 38°C. That time is calculated based on the difference of contained energy at the two temperatures, and the heat loss rate of the pipe. The temperature of the contain water may vary in reality due to reasons such as higher temperature delivered to the system, difference in ambient temperature, variation in tapping duration. The latter is considered when making the calculations as some water draw-offs are shorter than the time required for the whole water volume in the pipe to be displaced. The temperature in the pipe in such cases is calculated using a weighted average. The heat loss is adjusted to the average temperature of the pipe using the linear dependency between the heat loss and the temperature difference.

Comparing the primary energy use of the two systems show that the electrical wire uses a small fraction of the energy used for the DHW system with circulation. Furthermore, even when the energy used is converted to final energy using the primary energy factors (PEF) of 0.8 for district heating and 2.5 for electricity (2), the electrical wire uses a lesser amount of energy than the circulation system.



GRAPH 7.5 COMPARISON OF PRIMARY AND FINAL ENERGY

The electrical wire system could be beneficial to the overall performance of the system due to eliminating the need of a circulation loop and its high return temperature to the energy source. This allows for sufficient cooling of the return water on the primary side of the system, since energy is delivered to the secondary side only when tapping where the secondary side is fed with cold water of around 10°C.

8 FURTHER RESEARCH

As Denmark is aiming to reduce the use of fossil energy use over the coming years, new solutions and methods will be implemented in existing and new buildings in order to reduce the energy required for domestic hot water and space heating. According to Heat Plan Denmark (14) the District Heating will be further utilized in combination with renewable energy sources with a big focus on improving the efficiency within the network in regards to supply and return temperatures.

Standard design operating temperatures 70°C/40°C have been the point of several studies in the past which focused on the optimization of energy in new and renovated buildings. As the heating and DHW requirements are getting tighter approaching 2035, more and more new and conceptual solutions are being considered in the building energy sector. As suggested by Danfoss (15), such solutions could include lower temperatures for district heating networks and methods for using return hot water temperatures for various building systems.

8.1 LOW TEMPERATURE DISTRICT HEATING

The reduction of heat losses from District Heating is an issue that cannot be looked directly without also considering other factors such as comfort and health requirements when it comes to the use of Domestic Hot Water. For example, supplying DH water at lower temperatures might cause bacterial growth risks in hot water storage tank systems, as well as reduce the comfort for the occupants utilizing DHW from systems with storage tanks.

The main concern of introducing lower temperatures for preparation of DHW is the temperature requirements of keeping storage water at 60°C for reducing the risk of Legionella growth. With low district heating systems such as 55°C supply and 25°C return the required temperature levels at the tap can hardly be produced without some external heating of the domestic hot water. However, the German Standard W551 (16) states that hot water storage systems below 3 liters do not pose a risk for Legionella growth and are allowed for systems with instantaneous preparation of DHW.

Such systems can be considered as an alternative to more traditional DHW systems in new and existing buildings, such as the low temperature district heating flat stations tested at Lystrup, Denmark.(17) These stations provide individual preparation of DHW for each household in multistorey buildings utilizing the lower district heating supply temperature of 55°C for a tap water temperature at 45°C. The flat stations also eliminate the need for centralized DHW circulation, with minimal distribution pipe lengths to supply the apartment fixtures.

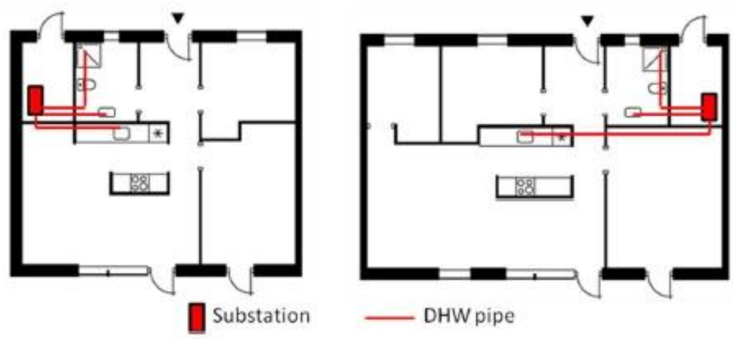


FIGURE 8.1 LAYOUT FOR FLAT STATIONS FOR DHW DISTRIBUTION PIPES [6]

Regarding the 10s waiting time at the furthest tap in the network, a flat station system might have an increased time for delivery of DHW at the tap, because of the lower operational temperatures, the hot water arrives at the tap at 40°C within 8.4 seconds from the start of tapping. (17) For a tap temperature of 45°C the waiting time is increased to 11 seconds. However, water at 35°C (which is a favorable temperature for hand washing and showering) is being delivered to the tap at 5.5 seconds. A possible subject of research could be the optimization and further improvement of this type of system with regards to decreasing the waiting time even more while still meeting the comfort criteria. Parameters such as pressure drops, heat transfer, pipe lengths, sizes and materials can be of interest in order to develop a more efficient operation. In addition, the implementation of decentralized low temperature district heating units in a low/zero energy building and analyzing the energy efficiency of the operation with regards to different user groups and profiles.

As a concept, this method aims to reduce the heat losses within the DH network but also involves higher investment costs. A financial analysis of those can be compared with the possible savings for the production of the DH required to run systems at lower temperatures.

8.2 FLOOR HEATING BYPASS FLOW OF RETURN WATER

The return temperatures for District Heating have a maximum requirement that is commonly specified as 40°C in most Danish districts. If the temperature exceeds that limit, it might result in additional costs to the consumers. This problem occurs often when buildings actually require high supply temperatures as well depending on their various heating installations or methods for preparation of DHW.

In order to further reduce the return temperature, a possible solution that involves utilizing the existing flow in a new direction from the building is to have a bypass for high return temperatures into a heating installation like small floor heating system in order to further reduce the water temperature.

To illustrate this concept, a simplified model is created in Polysun using the benchmark system established earlier in Chapter 5. On the primary side of the system, an additional loop is added that connects the return water to a small floor heating installation.

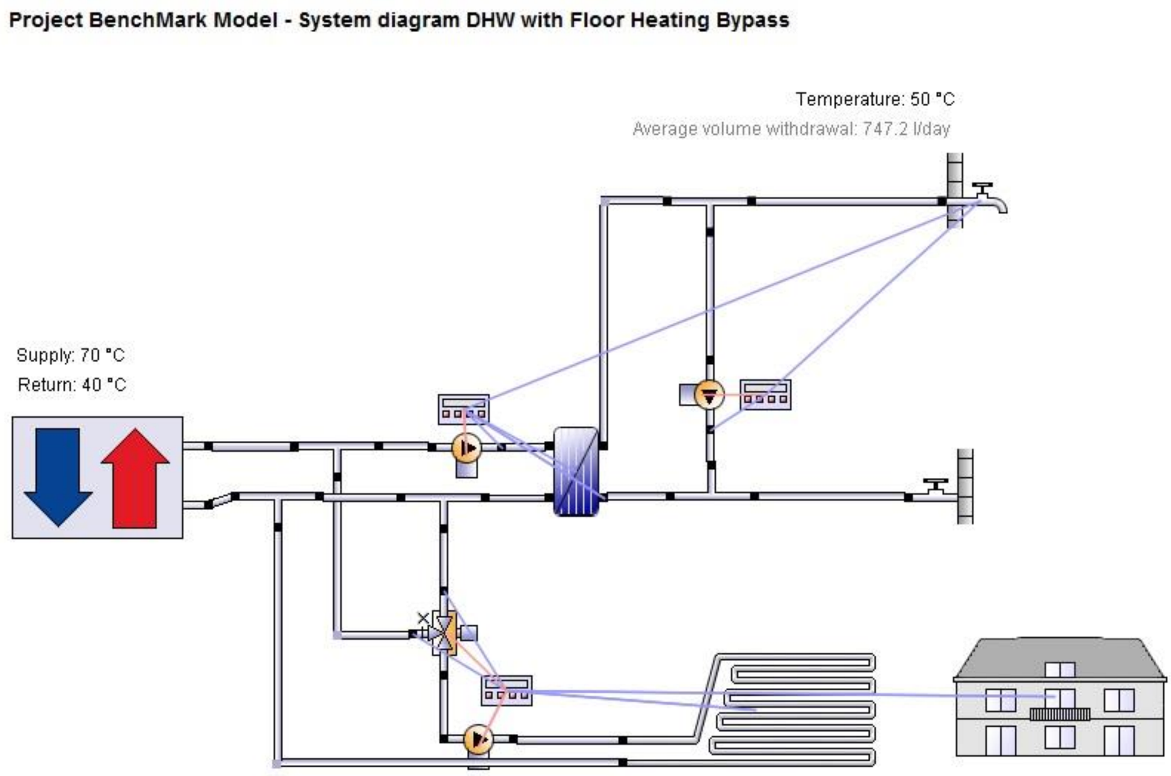


FIGURE 8.2 SYSTEM DIAGRAM FOR DHW WITH A FLOOR HEATING BYPASS

This concept makes an advantageous use of the return temperature on the primary loop whenever it exceeds 40°C. For the design building, a floor heating unit is chosen with the design values of 40/25. The inlet temperature output is controlled by the setpoint room temperature of 20°C. In order to ensure that the heating demand for this temperature is met, a 3-way valve is integrated which connects the return water with supply water from the main DH network in a mixing shunt. When the return water alone is not enough to provide the necessary heating output, it is mixed with supply hot water to reach the desired temperature. The operation of the water flow is performed by a controller which connects with temperature sensors for both the supply and return line from the network.

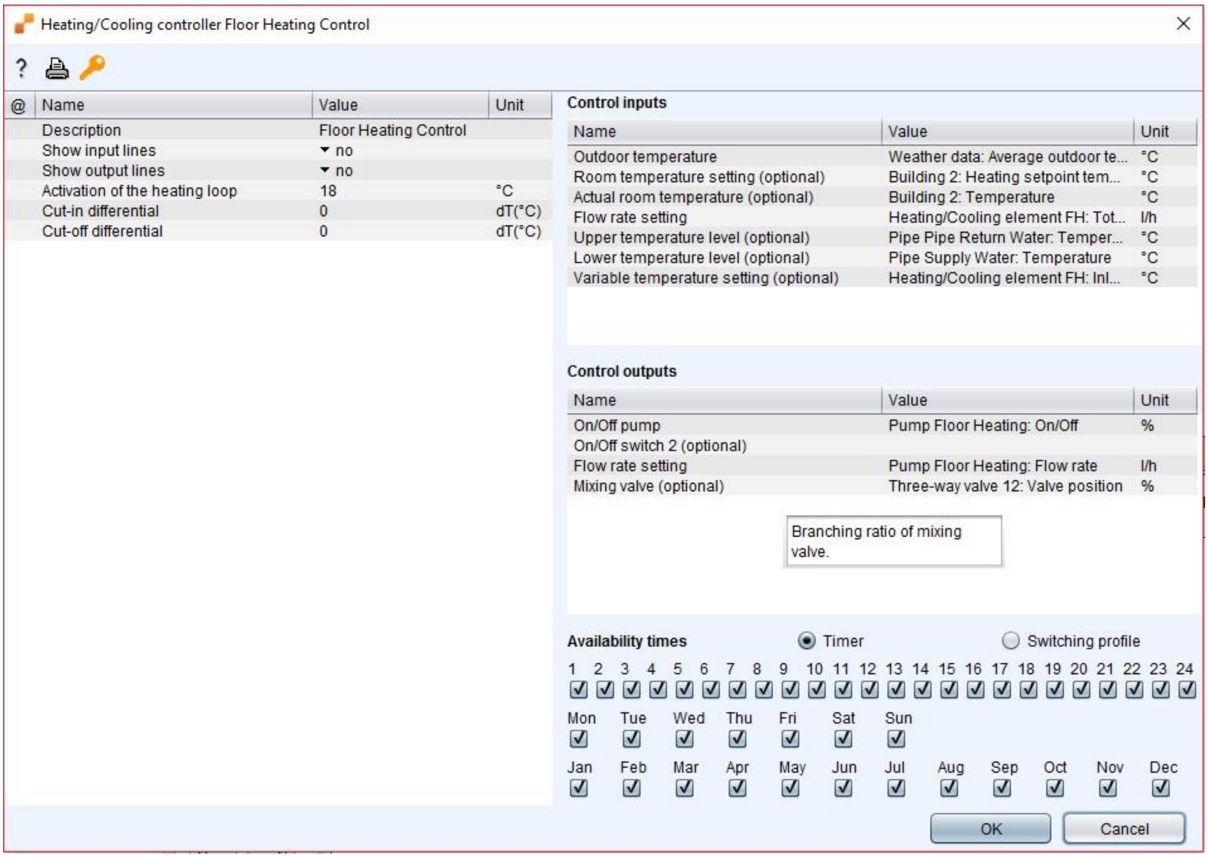
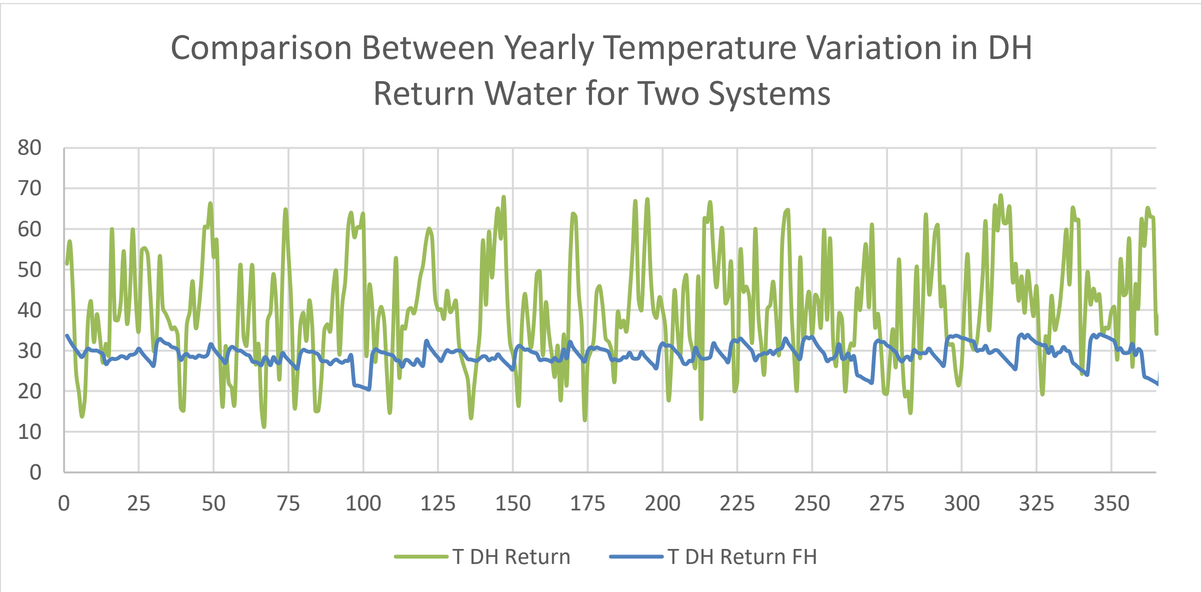


FIGURE 8.3 FLOOR HEATING CONTROLLER SETUP IN POLYSUN

The value of interest in this case is the return water temperature of this bypass solution compared to the benchmark system with no additional floor heating installed. The comparison between the variations of return temperatures for both cases is illustrated on:



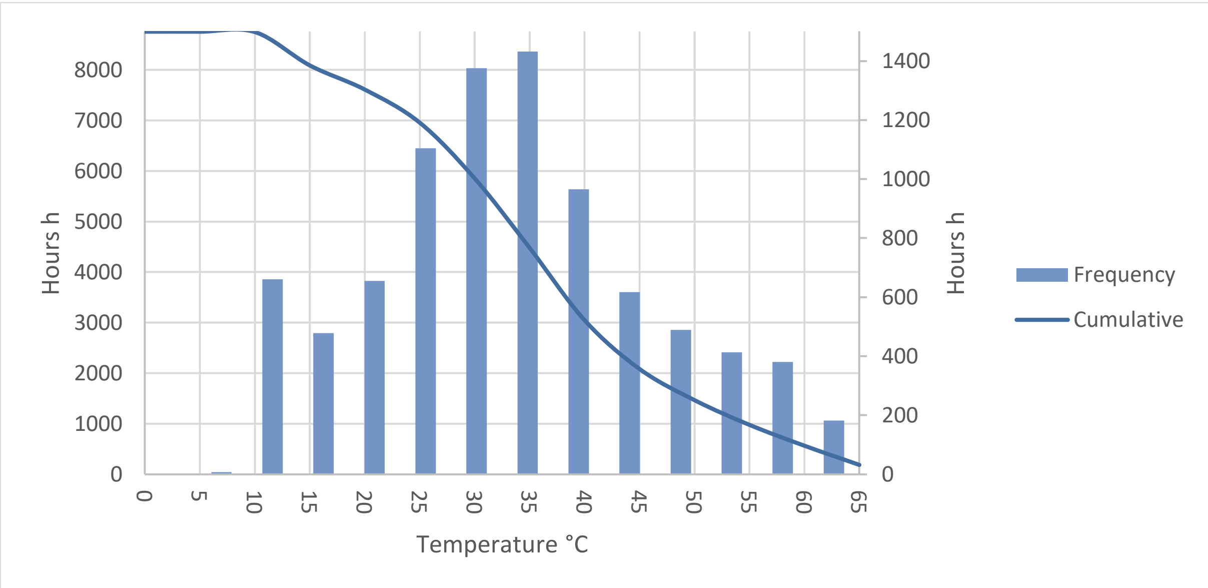
GRAPH 8.1 COMPARISON BETWEEN TEMPERATURE VARIATION IN DH RETURN WATER FOR BENCHMARK SYSTEM AND BYPASS SYSTEM

As can be expected, the return temperature for the bypass solution shows a much more stable fluctuation throughout the year because of the additional cooling of the return water. The average yearly DH return temperature is reduced from 36.1°C to 23.5°C, however, in the case of the benchmark system, there is a significant marginal variation because the temperatures fluctuate a lot more due to the tapping profiles being the only factor that influences the DH water utilization. The average, minimum and maximum temperatures for the benchmark system can be seen on Table 8.1:

	Yearly	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
AVG	36.1	38.3	37.1	35.8	35.3	33.2	33.8	36.0	33.7	34.5	36.6	38.5	40.6
MIN	10.5	11.4	10.1	9.5	9.3	10.0	10.6	10.8	11.5	11.3	10.6	11.0	10.3
MAX	57.8	58.3	58.7	57.8	56.8	57.7	57.9	57.5	58.9	57.3	57.4	57.2	58.1

TABLE 8.1 MONTHLY AVERAGE TEMPERATURES FOR DH RETURN WATER WITH MINIMUM AND MAXIMUM VALUES, BENCHMARK SYSTEM

Although on average the return water temperature throughout the year is below 40°C, there are still instances where the temperature exceeds the requirement value reaching up to 58.7°C. The number of hours in a year when the return temperature is above 40°C is 3046 h which is nearly 35% of the total number of operational hours in a year. This is illustrated on Graph 8.2:



GRAPH 8.2 CUMULATIVE DISTRIBUTION OF RETURN WATER TEMPERATURES OVER A YEAR FOR BENCHMARK SYSTEM

For a comparison, TABLE 8.2 represents the average, minimum and maximum temperatures for the simulated system with a floor heating bypass:

	Yearly	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
AVG	23.5	28.1	27.9	27	25	21.4	18.7	23.1	23.4	19.7	24.5	26.5	27.7
MIN	18.1	19.6	19.6	19.7	19.3	18	18	18	18	18	19.2	19.7	19.7
MAX	38.4	38.4	36.4	36.3	33.9	32.6	27.8	28.3	28.8	31.9	32.3	34.8	37

TABLE 8.2 MONTHLY AVERAGE TEMPERATURES FOR DH RETURN WATER WITH MINIMUM AND MAXIMUM VALUES, BYPASS SYSTEM

The results from the simulation suggest that the return temperature can be kept consistently lower throughout the year by redirecting the return flow through a floor heating system. Such solution can further reduce the heat losses in the DH network and optimize the use of hot water in floor heating systems operating in the range between 40-55°C supply and 25-30°C return.

As a point of further research could be the modelling and implementation of a similar system for low or zero energy buildings using simulation software such as IDA-ICE or TRANSYS. The used Polysun model allows for a simplified simulation testing and serves as a concept to showcase the possibility of utilizing higher return water temperatures from DHW systems. However, due to its limitations as discussed earlier in this report, further development of such model should be conducted more thoroughly with the help of more advanced software tools.

9 CONCLUSION

This study consists of two main parts - discussing the domestic hot water use, in relation to user behavior, and domestic hot water system performance, as well as the link between the two. Domestic hot water use varies significantly as a result of the influence of different factors. That is concluded from the analysis of measurements for a period of over 3 years for a multistorey student accommodation building consisting of 99 apartments. The daily use per apartment varies between 0 – 289 l/d. Furthermore, based on the analysis of the use for the case building, a seasonal variation of consumption is observed. The magnitude of the variation is close to 40 % from the yearly average in summer and close to 25% for winter. Monthly factors are derived based on the available data. Such information can be particularly useful when designing solar thermal installations, as it has also concluded in other studies.

Additionally, a variation from week days to weekends is observed, where on average throughout the year the consumption during week days is 6-8% higher than the consumption during weekends. That opposes findings from other studies on the matter, where the hot water consumption during weekend showed to be higher. Those studies, however where done based on a more general user group, whereas for this analysis, the data is based on user group of more specific type, having in mind the use of the building. That contradiction again confirms the conclusion that the hot water use is influenced by various factors, some of which are difficult to quantify. The specific user group also shows seasonal variation in the hot water use, when occupant absences are disregarded. Conclusion based on the assumption that lower consumptions in some periods could be due to the occupants' absence. However arguable, the analysis shows that the water use is slightly higher in winter and lower in summer compared to the yearly average. Furthermore, it shows that during winter periods larger daily volumes of water are used more frequently, where in summer periods, the smaller volumes water used per day are occurring more often.

Analyzing domestic hot water systems with active circulation loops leads to several conclusions. Domestic hot water systems' performance is sensitive to the user behavior. That is particularly valid for systems with circulation. Building energy simulation modelling of several different systems using input parameters and data from the available measurements suggests that the placement of the temperature sensor has an effect on the overall energy use for the system. Placing the sensor before the circulation loops seems to show a much more stable distribution of the hot water temperature and in the case of the modelled system leads up to an 18% reduction of the total energy use. Heat losses from recirculation of hot water could possibly be reduced by turning off the circulation pump when it is not needed if the systems control strategy allows for a dynamic operation based on logging the hot water consumption and creating a profile based on the usage pattern.

Comparing a system with a storage tank with the same boundary conditions for the modelled building suggests that the placement of the temperature sensor also has an effect on the total energy consumption. The simulated storage tank system showed a 14% higher energy use than the system with a heat exchanger similar to the case building, while still being able to meet the same demand for the same user profiles and monthly consumption values. In addition, the storage tank system is able to return the water to the district heating with lower temperatures more often, with 28% less hours per year when the return temperature exceeds the design value of 40°C.

Several systems can offer a solution in response to the ever-changing energy requirements as Denmark is further approaching the independency of fossil fuel energy. Lowering the standard operating temperatures from the District Heating could be a significant issue for standard systems for production and delivery of domestic hot water. However, smaller systems with substations could eliminate the necessity for water recirculation and reduce the heat losses in a more typical piping network, while also being able to comply with health requirements by keeping the stored hot water below 3L and thus preventing the growth of Legionella. On the other hand, high return temperatures could be utilized by being delivered to a floor heating system and thus cooled down additionally while providing more comfort to the users in a more efficient way.

LIST OF FIGURES

REFERENCE LIST

1. Varmt Brugsvand. 2009.

2. Energistyrelsen.

3. Ahmed K, Pylsy P, Kurnitski J. Monthly domestic hot water profiles for energy calculation in Finnish apartment buildings. Energy Build [Internet]. Elsevier B.V.; 2015;97:77–85. Available from: http://dx.doi.org/10.1016/j.enbuild.2015.03.051

4. Ahmed K, Pylsy P, Kurnitski J. Monthly domestic hot water profiles for energy calculation in Finnish apartment buildings. Energy Build. Elsevier B.V.; 2015;97:77–85.

5. Ahmed K, Pylsy P, Kurnitski J. Hourly consumption profiles of domestic hot water for different occupant groups in dwellings. 2016;137:516–30.

6. Rodríguez-Hidalgo MC, Rodríguez-Aumente PA, Lecuona A, Legrand M, Ventas R. Domestic hot water consumption vs. solar thermal energy storage: The optimum size of the storage tank. Appl Energy. 2012;97:897–906.

7. Dansk Standard. Termisk isolering af tekniske installationer Thermal insulation of technical service and. 2013;42.

8. Bygningsreglement.

9. Heat Exchangers ,PHE.

10. McDade JE. Legionella and the Prevention of Legionellosis. Emerg Infect Dis. 2008;14:1006.

11. Ag VS. PolySun User Guide. 2016;

12. Heat Loss Insulated Pipe Equation and Calculator | Engineers Edge | www.engineersedge.com.

13. Dansk Standard. Norm for vandinstallationer Code of Practice for domestic water supply. 2009;75.

14. Denmark R. Heat Plan Denmark Heat Plan Denmark by Anders Dyrelund Heat Plan Denmark by Anders Dyrelund. 2009;1–14.

15. Utilization-of-return-water-in-district-heating-networks---Oddgeir---v2 (4).

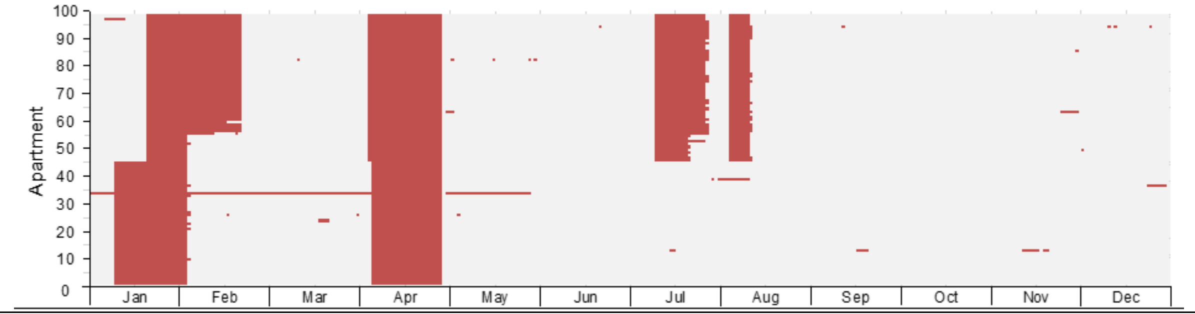
16. Gerhardy K. Das DVGW-Arbeitsblatt W 551 und die 3-Liter-Regel. Energ Wasser Prax. 2012;(2):42–5.

17. Brand M. Heating and Domestic Hot Water Systems in Buildings Supplied by Low-Temperature District Heating [Internet]. 2013. 157 p. Available from: http://www.byg.dtu.dk/-/media/Institutter/Byg/publikationer/PhD/byg-r296.ashx?la=da

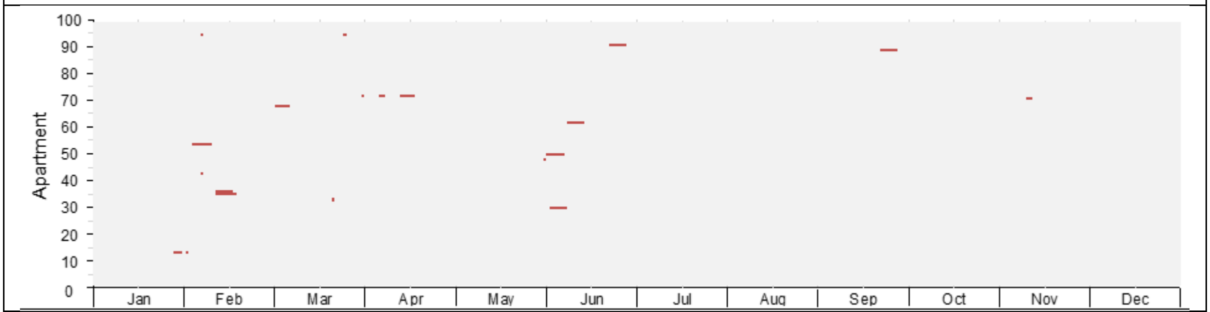
APPENDIX A DATA AVAILABILITY

Illustration of data availability for the years 2013, 2014, 2015 and 2016 expressed in daily values.

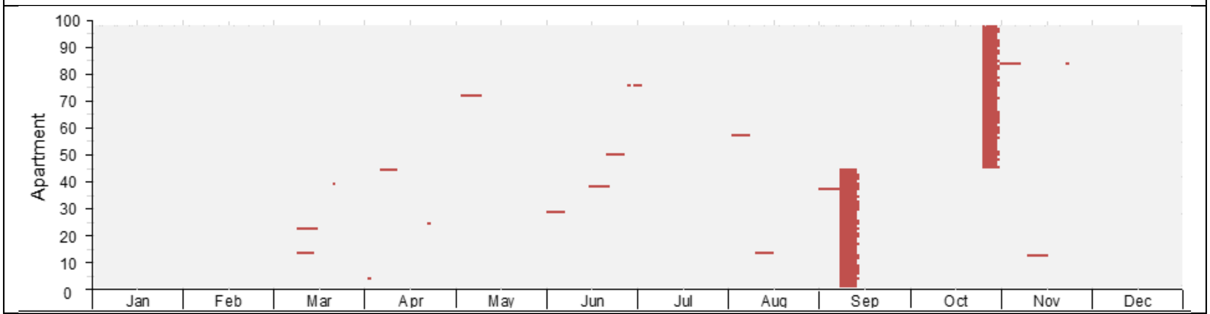
2013



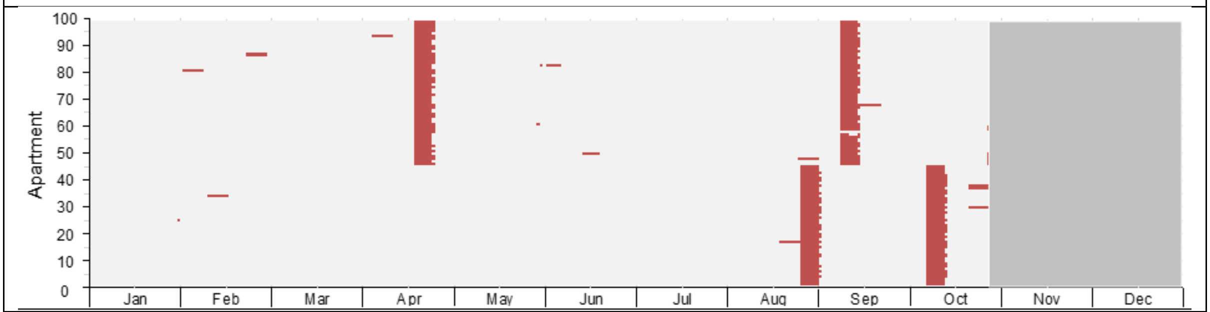
2014



2015



2016



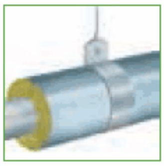
APPENDIX B DAILY DHW CONSUMPTION PER PERSON

The number of registered people in each apartment was noted down during a site visit. Assuming that the same composition of the occupants has been the same for the whole year, average daily consumption for the respective apartments was generated. The apartments were grouped by the registered number of people and plotted. Expectedly the variation is consumption for both groups is great and the total average of the two come close. If the assumption for the number of people in each apartment during 2016 is correct, then the plot confirms that DHW consumption for a household of 1 can be close to that for a household of 2. Furthermore, the spread of the values for the two groups overlap to a great extent, which indicates once again that in some instances a household of two can use less DHW than a household of two.

APPENDIX C PIPE INSULATION LEVEL ACCORDING TO STANDARDS

Klasse 4

Isolerede bæringer med fuld isoleringstykkelse



Korrekte isoleringstykkelser med isolerede bæringer

Rørdiameter 15 til 140 mm, klasse 4

Produkt	Temperaturforskel (°C)									
	20	30	40	50	60	70	80	90	100	110
Rørdiam. 15 mm:										
Universal Rørskål	20	20	20	20	20	20	30	30	30	30
Rørskål 800	20	20	20	20	20	20	20	20	20	20
Lamelmåtte	20	20	20	20	30	30	30	30	30	30
Rørdiam. 18 mm:										
Universal Rørskål	20	20	20	30	30	30	30	30	30	30
Rørskål 800	20	20	20	20	20	20	20	20	20	20
Lamelmåtte	20	20	30	30	30	30	30	30	40	40
Rørdiam. 22 mm:										
Universal Rørskål	20	30	30	30	30	30	30	40	40	40
Rørskål 800	20	20	20	20	20	20	20	30	30	30
Lamelmåtte	30	30	30	30	30	40	40	40	40	40
Rørdiam. 28 mm:										
Universal Rørskål	30	30	30	30	40	40	40	40	40	50
Rørskål 800	20	20	30	30	30	30	30	30	30	30
Lamelmåtte	30	30	40	40	40	40	40	50	50	50

Image referance: Rockwool.dk

Table for calculation of the minimum insulation thickness according to specific insulation class as a function of temperature difference. For the system in the case study ¾" pipes are chosen, with inner diameter of 22mm. For a temperature difference of 30-40°C between the water temperature and the space, which accommodates the pipe the minimum insulation level is 30mm of universal round pipe insulation.

APPENDIX D HEAT EXCHANGER EFFECT

For systems with heat exchangers, the proper sizing of latter is of great importance as the power maximum power output must be able to cover the peak demands in the building. For the sizing of the heat exchanger the maximum required effect is calculated. That is according to the maximum nominal effect, adjusted with heat losses from the unit and a safety factor taking into account the collection of hard particles on the inner surfaces of the heat exchanger.

$$P_{final} = (P_{eff} + P_{losses} + P_{circ}) * f_p$$

Where:
P_{final} [W] is the design maximum power output from the heat exchanger
P_{eff} [W] is the nominal effect of the heat exchanger that is required according to the water demand
P_{losses} [W] is the heat losses from the heat exchanger
F_p [-] is a safety factor accounting for collection of hard particles on the inner surface of the heat exchanger (typicaly between 1.1-1.5)

EQUATION 9.1

$$P_{eff} = \dot{m} * Cp * (T_h - T_c)$$

Where:
m [kg/s] is the water mass flow through the secondary side
C_p [KJ/kg*K] is the specific heat capacity of water
T_h [K] is the required hot water temperature
T_c [K] is the cold water temperature

EQUATION 9.2

However, for multiple apartments the nominal power can be estimated by using a calculation, which accounts for the number of apartments, taps and occupants. Since there are multiple apartments for which the power output of the system needs to be calculated, it is highly unlikely that water withdraw occurs simultaneously in all of them. The method, based on the German standard DIN 4708 and referred by Danish Technological Institute (DTI) and DS 439 accounts for this unlikelihood.

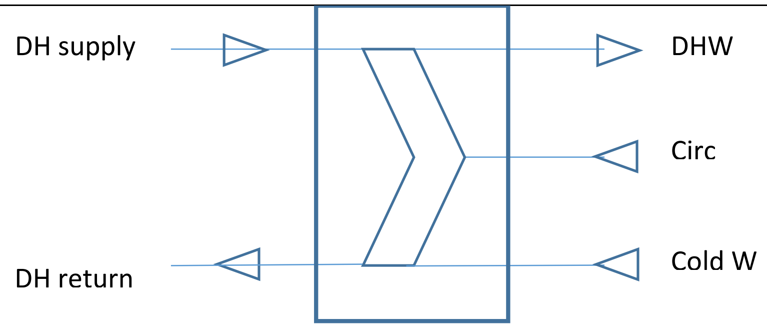


FIGURE 9.1 SCHEMATICAL REPRESENTATION OF A HEAT EXCHANGER

$$P_{eff} = 1.19 * N + 18.8 * \sqrt{N} + 17.6$$

$$N = \frac{\sum(n * p * v * E)}{3.5 * 4.36}$$

Where:
N [-] is the number of "normal" apartments
n [-] is number of apartments
p [-] is number of occupants
E [kWh] is the estimated energy use for tapping unit according to the standard
v [-] is the number of tapping units in an apartment

Values used in the calculation:

- 10 apartments (identical apartments)
- 2 occupants per apartment (according to standard)
- 1 bathroom per apartment – estimated energy use 4.36 kWh
- Temperatures on primary side supply – 70°C; return – 40°C
- Water temperature set point – 50°C
- Minimum temperature on the return water from circulation – 38°C
- Losses in the heat exchanger 0.7 kW
- Losses in circulation 0.3 kW/normal apartment
- Safety factor f_p = 1.3

Apartment type	Nr. of apartments	Nr. occupants p. apartment	Nr. tapping units	Energy demand p. apar.	Total energy demand
	n	*p*	*v*	*e [kWh]*	*n*p*v*E [kWh]*
2-room	10	2	1 – shower	4.36	87.2

$$N = \frac{87.2}{3.5 * 4.36} = \mathbf{5.72}$$

From the formula, the number of "normal" apartments is 5.72

$P_{eff} = 1.19 * N + 18.8 * \sqrt{N} + 17.6$ $P_{eff} = 1.19 * 5.72 + 18.8 * \sqrt{5.72} + 17.6 = 69.52$	[kW]
$P_{eff} = 69.52 \text{ kW}$ $P_{circ} = 0.3 * 5.72 = 1.72 \text{ kW}$	
$P_{final} = (P_{eff} + P_{losses} + P_{circ}) * f_p$ $P_{final} = (69.52 + 0.7 + 1.72) * 1.3 = \mathbf{93.5}$	[kW]

$q_v = \dfrac{P_{eff}}{C_p * (T_{DHW} - T_C)}$	[l/s]
$q_c = \dfrac{P_{circ}}{C_p * (T_{DHW} - T_{circ.return})}$	[l/s]
$q_{sec} = q_v + q_c$	[l/s]
$T_{sec.supply} = \dfrac{q_v * T_C + q_c * T_{circ.return}}{q_v + q_c}$	[°C]
$q_{prim} = \dfrac{P_{final}}{C_p * (T_{DHsupply} - T_{DHreturn})}$	[l/s]

$q_v = \dfrac{69.52}{4.2 * (50 - 10)} = 0.41$
$q_c = \dfrac{1.72}{4.2 * (50 - 38)} = 0.03$
$q_{sec} = 0.41 + 0.03 = 0.44$
$T_{sec.supply} = \dfrac{0.41 * 10 + 0.03 * 38}{0.41 + 0.03} = 11.9$ $T_{P\ return}$ >5°C+$T_{S\ supply}$; $T_{P\ return}$ = 11.9+5 =16.9
$q_{prim} = \dfrac{93.5}{4.2 * (70 - 16.9)} = 0.42$

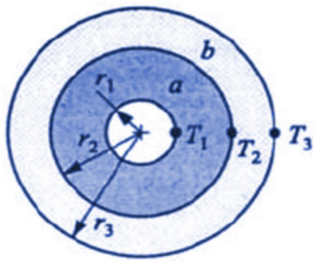
APPENDIX E PIPE HEAT LOSS CALCULATIONS

C:\Users\Plamen\Google Drive\Master Thesis\02_WORK\01_SPREAD SHEETS\Pipe heat loss Calc (for EL-tracing)

User Input

Emperical determination of pipe heat loss

r1	r in	**0.01 m**	
r2	r out	**0.01 m**	
r3	r ins	**0.04 m**	
	k insu	**0.04 W/m·K**	
	k steel	**16.50 W/m·K**	
	L	**40.00 m**	
	Tin	**50.0°C**	
	Tout	**10.0°C**	
	ho	**25 W/m²·K**	{ =1/0.04}



$$Q = \frac{2\pi L(T_o - T_i)}{\frac{\ln\left(\frac{r_2}{r_1}\right)}{k_{steel}} + \frac{\ln\left(\frac{r_3}{r_2}\right)}{k_{insu}} + \frac{1}{h_o r_3}}$$

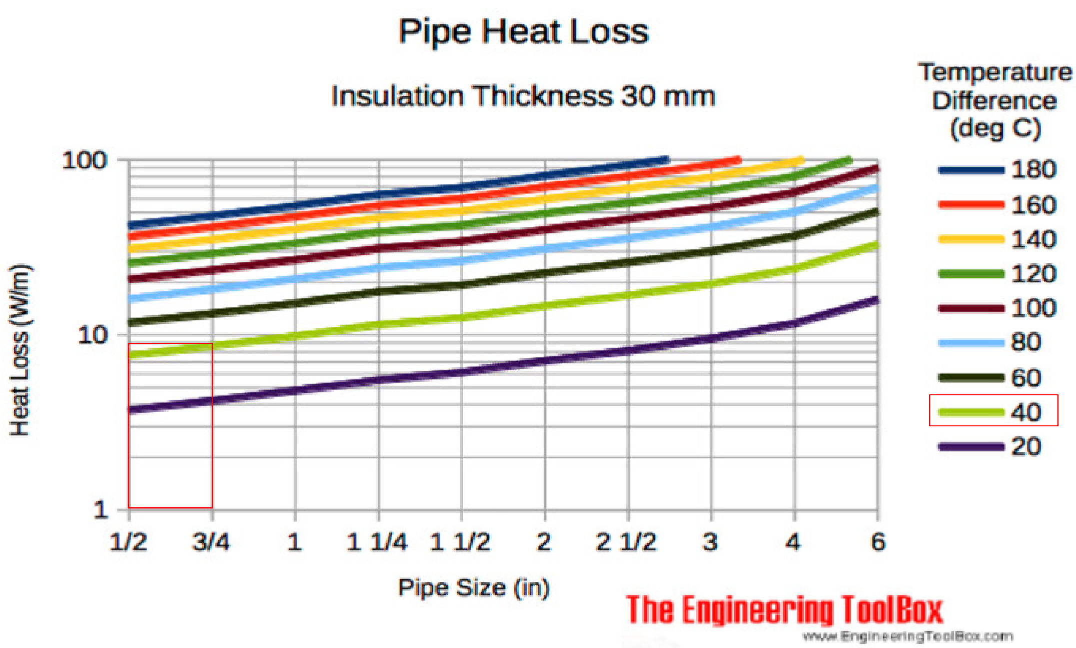
	ln(r2/r1)	0.19	{ =LN(0.013/0.011)}	2πL(Ti-To)	10053.096
	ln(r3/r2)	1.17	{ =LN(0.043/0.013)}		
	ln(r2/r1)/k steel	0.01	{ =0.188/16.5}		
	ln(r3/r2)/k insu	32.57	{ =1.173/0.036}		
	1/h0*r3	0.92	{ =1/(25*0.043)}		
	Q (dT=40°C)	-7.50 W/m	{ =(2*PI()*(10-50))/(0.011+32.573+0.921)}	Q (dT=28°C)	-5.3 W/m
1.	Q tot	-300 W	{ =-7.5*40}	Q tot	-210 W
2.		-767316365 J	{ =-300*2557320.3}		
3.		-213.15 kWh	{ =-767316365*0}		

1 Joule =	2.78E-07	kWh

		@ dT=40°C		@ dT=28°C	
Months	still time [s]	E [J]	kWh	E [J]	kWh
1	2557320	-7.67E+08	-213.15	-5.37E+08	-149.20
2	2301019	-6.9E+08	-191.78	-4.83E+08	-134.25
3	2550530	-7.65E+08	-212.58	-5.36E+08	-148.81
4	2483712	-7.45E+08	-207.01	-5.22E+08	-144.91
5	2562179	-7.69E+08	-213.55	-5.38E+08	-149.49
6	2490735	-7.47E+08	-207.60	-5.23E+08	-145.32
7	2613617	-7.84E+08	-217.84	-5.49E+08	-152.49
8	2591178	-7.77E+08	-215.97	-5.44E+08	-151.18
9	2482614	-7.45E+08	-206.92	-5.21E+08	-144.84
10	2564421	-7.69E+08	-213.74	-5.39E+08	-149.62
11	2470931	-7.41E+08	-205.94	-5.19E+08	-144.16
12	2575819	-7.73E+08	-214.69	-5.41E+08	-150.28
			-2521 kWh		**-1765 kWh**

User Input

Graphical determination of pipe heat loss



	@ dT=40°C	@ dT=28°C	
Q	8.5 W/m	5.20 W/m	For indoor conditions reduce value from reading with 10%
Q tot	340 W	208 W	

Months	Still time [s]	E [J]	@ dT=40°C		@ dT=28°C
1	2557320	8.69E+08	241.53	5.32E+08	1.48E+02
2	2301019	7.82E+08	217.32	4.79E+08	1.33E+02
3	2550530	8.67E+08	240.89	5.31E+08	1.47E+02
4	2483712	8.44E+08	234.57	5.17E+08	1.44E+02
5	2562179	8.71E+08	241.99	5.33E+08	1.48E+02
6	2490735	8.47E+08	235.24	5.18E+08	1.44E+02
7	2613617	8.89E+08	246.84	5.44E+08	1.51E+02
8	2591178	8.81E+08	244.72	5.39E+08	1.50E+02
9	2482614	8.44E+08	234.47	5.16E+08	1.43E+02
10	2564421	8.72E+08	242.20	5.33E+08	1.48E+02
11	2470931	8.4E+08	233.37	5.14E+08	1.43E+02
12	2575819	8.76E+08	243.27	5.36E+08	1.49E+02
			2856 kWh		**1747 kWh**

	PE	FE
BM - Circul	3269 kWh	2615 kWh
EL @ dT=4(	2521 kWh	6302 kWh
EL @ dT=2ξ	1765 kWh	4411 kWh

PF - BR15	
Electricity	2.5
DH	0.8

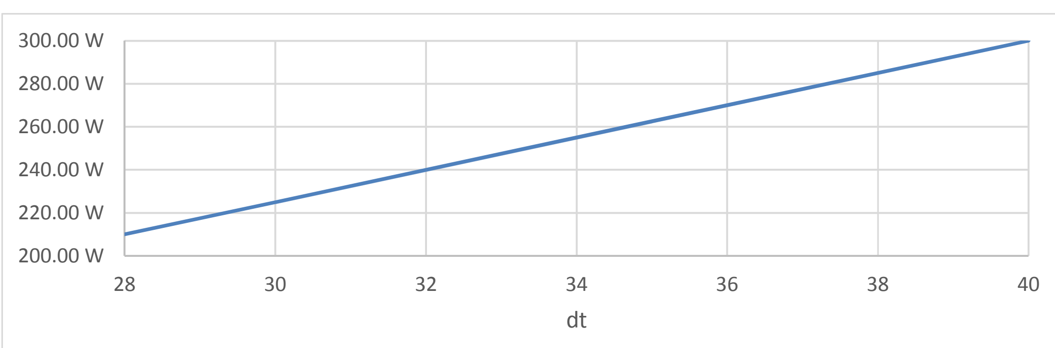
User Input

Heat loss calculation (adjusted to AVG water temp.)

	MONTH											
C	1	2	3	4	5	6	7	8	9	10	11	12
1	29	31	30	26	27	25	15	21	27	27	29	24
2	20	22	21	19	19	18	11	15	19	19	21	17
3	23	24	24	21	22	20	12	16	21	21	23	19
4	69	75	73	64	66	60	37	50	65	65	71	59
5	160	173	169	148	153	138	85	115	149	150	165	135
6	285	308	301	263	273	246	152	205	266	268	294	241
7	309	333	326	285	296	267	165	222	288	290	319	261
8	260	281	274	240	249	224	139	187	242	245	268	220
9	194	210	205	179	186	168	104	140	181	183	201	164
10	155	168	164	144	149	134	83	112	145	146	161	132
11	146	158	154	135	140	126	78	105	136	138	151	124
12	143	154	151	132	137	123	76	103	133	134	147	121
13	144	156	152	133	139	125	77	104	135	136	149	122
14	153	166	162	142	147	133	82	111	143	144	159	130
15	168	182	178	156	162	145	90	121	157	158	174	143
16	214	231	226	198	205	185	115	154	200	201	221	181
17	269	291	284	249	258	232	144	194	251	253	278	228
18	310	335	328	287	298	268	166	223	290	292	320	263
19	285	308	301	264	274	246	153	205	266	268	295	242
20	211	228	223	195	203	183	113	152	197	199	218	179
21	143	155	151	132	138	124	77	103	134	135	148	121
22	101	109	107	93	97	87	54	73	94	95	105	86
23	68	74	72	63	66	59	37	49	64	64	71	58
24	46	49	48	42	44	39	24	33	43	43	47	39

Example	Time duration for displacing contained water volume in the pipe	78 s	
	Contained water volume in pipes	15.6 l	
	Water flow rate at tapping	0.2 l/s	
	Draw off duration	29 s	
	Displaced volume at drawoff	5.80 l	*{ =29*0.2}*
	AVGw t°C	42.5°C *{ =((5.8*50)+((15.61-5.8)*38))/15.61}*	

Pipe heat loss adjusted according to temperature differnce **Q loss**
(dt is based on AVGw temp. of the water in the pipe and ambiant temp.)



Pipe heat loss

E @42.5 2784459 J *{ =4200*15.61*42.46}*
E @38 2492139 J *{ =4200*15.61*38}*

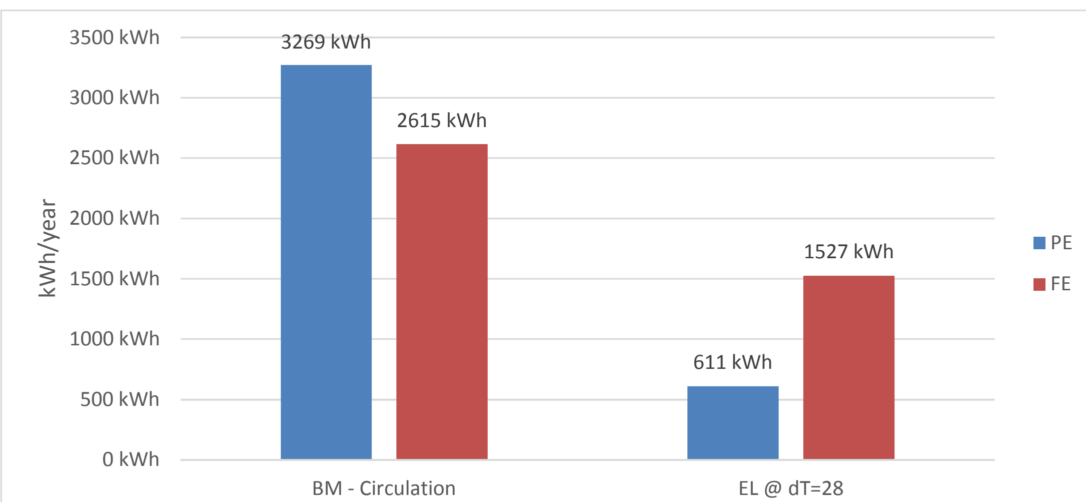
E@42.5 -E@38 292320 J *{ =2784459-2492139}*

t cooling = dE/Qloss **1218 s**

Pipe heat loss at 38°C = 210 W

Months	Total stand still duration [s]	Energy @ dT=28°C [J]	Energy @ dT=28°C [kWh]
1	871087	1.83E+08	50.81
2	797308	1.67E+08	46.51
3	879187	1.85E+08	51.29
4	832389	1.75E+08	48.56
5	865291	1.82E+08	50.48
6	824011	1.73E+08	48.07
7	1100358	2.31E+08	64.19
8	906678	1.9E+08	52.89
9	833699	1.75E+08	48.63
10	862617	1.81E+08	50.32
11	847634	1.78E+08	49.45
12	849021	1.78E+08	49.53
			611 kWh

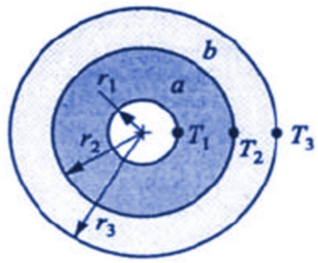
	PE	FE
BM - Circul	3269 kWh	2615 kWh
EL @ dT=28	611 kWh	1527 kWh



User Input

Emperical determination of pipe heat loss

r1	r in	0.01 m	
r2	r out	0.01 m	
r3	r ins	0.04 m	
	k insu	0.04 W/m·K	
	k steel	16.50 W/m·K	
	L	40.00 m	
	Tin	50.0°C	
	Tout	10.0°C	
	ho	25 W/m²·K	{ =1/0.04}



$$Q = \frac{2\pi L(T_o - T_i)}{\frac{\ln\left(\frac{r_2}{r_1}\right)}{k_{steel}} + \frac{\ln\left(\frac{r_3}{r_2}\right)}{k_{insu}} + \frac{1}{h_o r_3}}$$

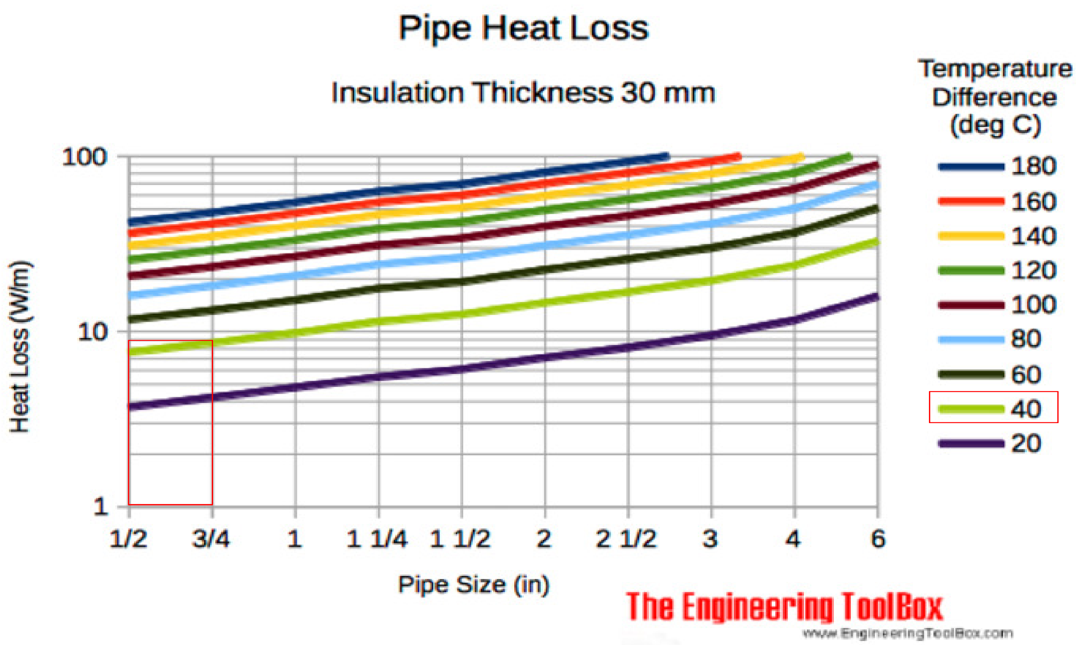
	ln(r2/r1)	0.19	{ =LN(0.013/0.011)}	2πL(Ti-To)	10053.096
	ln(r3/r2)	1.17	{ =LN(0.043/0.013)}		
	ln(r2/r1)/k steel	0.01	{ =0.188/16.5}		
	ln(r3/r2)/k insu	32.57	{ =1.173/0.036}		
	1/h0*r3	0.92	{ =1/(25*0.043)}		
	Q (dT=40°C)	-7.50 W/m	{ =(2*PI()*(10-50))/(0.011+32.573+0.921)}	Q (dT=28°C)	-5.3 W/m
1.	Q tot	-300 W	{ =-7.5*40}	Q tot	-210 W
2.		-767316365 J	{ =-300*2557320.3}		
3.		-213.15 kWh	{ =-767316365*0}		

1 Joule =	2.78E-07 kWh

		@ dT=40°C		@ dT=28°C	
Months	still time [s]	E [J]	kWh	E [J]	kWh
1	2557320	-7.67E+08	-213.15	-5.37E+08	-149.20
2	2301019	-6.9E+08	-191.78	-4.83E+08	-134.25
3	2550530	-7.65E+08	-212.58	-5.36E+08	-148.81
4	2483712	-7.45E+08	-207.01	-5.22E+08	-144.91
5	2562179	-7.69E+08	-213.55	-5.38E+08	-149.49
6	2490735	-7.47E+08	-207.60	-5.23E+08	-145.32
7	2613617	-7.84E+08	-217.84	-5.49E+08	-152.49
8	2591178	-7.77E+08	-215.97	-5.44E+08	-151.18
9	2482614	-7.45E+08	-206.92	-5.21E+08	-144.84
10	2564421	-7.69E+08	-213.74	-5.39E+08	-149.62
11	2470931	-7.41E+08	-205.94	-5.19E+08	-144.16
12	2575819	-7.73E+08	-214.69	-5.41E+08	-150.28
			-2521 kWh		**-1765 kWh**

User Input

Graphical determination of pipe heat loss



	@ dT=40°C	@ dT=28°C	
Q	8.5 W/m	5.20 W/m	For indoor conditions reduce value from reading with 10%
Q tot	340 W	208 W	

Months	Still time [s]	E [J]	@ dT=40°C		@ dT=28°C
1	2557320	8.69E+08	241.53	5.32E+08	1.48E+02
2	2301019	7.82E+08	217.32	4.79E+08	1.33E+02
3	2550530	8.67E+08	240.89	5.31E+08	1.47E+02
4	2483712	8.44E+08	234.57	5.17E+08	1.44E+02
5	2562179	8.71E+08	241.99	5.33E+08	1.48E+02
6	2490735	8.47E+08	235.24	5.18E+08	1.44E+02
7	2613617	8.89E+08	246.84	5.44E+08	1.51E+02
8	2591178	8.81E+08	244.72	5.39E+08	1.50E+02
9	2482614	8.44E+08	234.47	5.16E+08	1.43E+02
10	2564421	8.72E+08	242.20	5.33E+08	1.48E+02
11	2470931	8.4E+08	233.37	5.14E+08	1.43E+02
12	2575819	8.76E+08	243.27	5.36E+08	1.49E+02
			2856 kWh		**1747 kWh**

	PE	FE
BM - Circul	3269 kWh	2615 kWh
EL @ dT=4(	2521 kWh	6302 kWh
EL @ dT=2ɛ	1765 kWh	4411 kWh

PF - BR15	
Electricity	2.5
DH	0.8

User Input

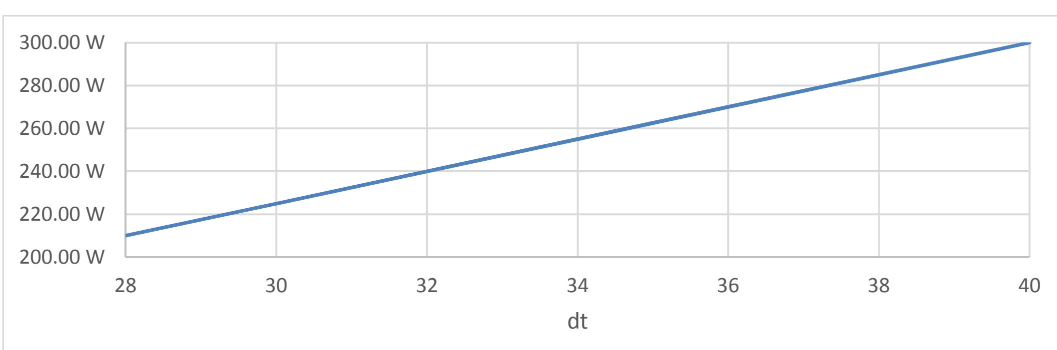
Heat loss calculation (adjusted to AVG water temp.)

	MONTH											
C	1	2	3	4	5	6	7	8	9	10	11	12
1	29	31	30	26	27	25	15	21	27	27	29	24
2	20	22	21	19	19	18	11	15	19	19	21	17
3	23	24	24	21	22	20	12	16	21	21	23	19
4	69	75	73	64	66	60	37	50	65	65	71	59
5	160	173	169	148	153	138	85	115	149	150	165	135
6	285	308	301	263	273	246	152	205	266	268	294	241
7	309	333	326	285	296	267	165	222	288	290	319	261
8	260	281	274	240	249	224	139	187	242	245	268	220
9	194	210	205	179	186	168	104	140	181	183	201	164
10	155	168	164	144	149	134	83	112	145	146	161	132
11	146	158	154	135	140	126	78	105	136	138	151	124
12	143	154	151	132	137	123	76	103	133	134	147	121
13	144	156	152	133	139	125	77	104	135	136	149	122
14	153	166	162	142	147	133	82	111	143	144	159	130
15	168	182	178	156	162	145	90	121	157	158	174	143
16	214	231	226	198	205	185	115	154	200	201	221	181
17	269	291	284	249	258	232	144	194	251	253	278	228
18	310	335	328	287	298	268	166	223	290	292	320	263
19	285	308	301	264	274	246	153	205	266	268	295	242
20	211	228	223	195	203	183	113	152	197	199	218	179
21	143	155	151	132	138	124	77	103	134	135	148	121
22	101	109	107	93	97	87	54	73	94	95	105	86
23	68	74	72	63	66	59	37	49	64	64	71	58
24	46	49	48	42	44	39	24	33	43	43	47	39

Example	Time duration for displacing contained water volume in the pipe	78 s	
	Contained water volume in pipes	15.6 l	
	Water flow rate at tapping	0.2 l/s	
	Draw off duration	29 s	
	Displaced volume at drawoff	5.80 l	*{ =29*0.2}*

AVGw t°C 42.5°C *{ =((5.8*50)+((15.61-5.8)*38))/15.61}*

Pipe heat loss adjusted according to temperature differnce **Q loss**
(dt is based on AVGw temp. of the water in the pipe and ambiant temp.)



Pipe heat loss

User Input

E @42.5 2784459 J *{ =4200*15.61*42.46}*
E @38 2492139 J *{ =4200*15.61*38}*

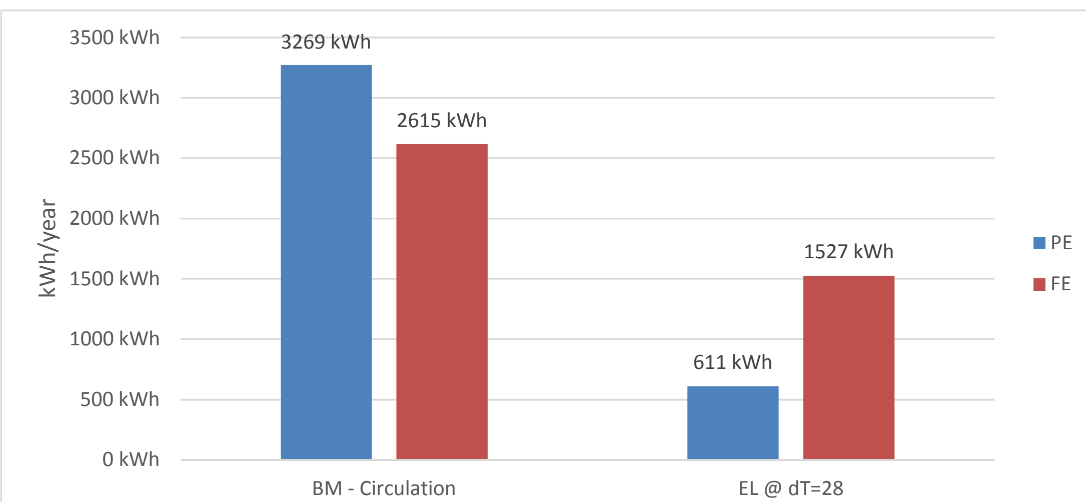
E@42.5 -E@38 292320 J *{ =2784459-2492139}*

t cooling = dE/Qloss **1218 s**

Pipe heat loss at 38°C = 210 W

Months	Total stand still duration [s]	Energy @ dT=28°C [J]	Energy @ dT=28°C [kWh]
1	871087	1.83E+08	50.81
2	797308	1.67E+08	46.51
3	879187	1.85E+08	51.29
4	832389	1.75E+08	48.56
5	865291	1.82E+08	50.48
6	824011	1.73E+08	48.07
7	1100358	2.31E+08	64.19
8	906678	1.9E+08	52.89
9	833699	1.75E+08	48.63
10	862617	1.81E+08	50.32
11	847634	1.78E+08	49.45
12	849021	1.78E+08	49.53
			611 kWh

	PE	FE
BM - Circul	3269 kWh	2615 kWh
EL @ dT=2ε	611 kWh	1527 kWh



Water draw duration

Calculated water stand still duration for each hour

1 1

C:\Users\Plamen\Google Drive\Master Thesis\02_WORK\01_SPREAD SHEETS\Pipe heat loss Calc (for EL-tracing)

MONTH

HOURS

Colu	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
1	3571	3569	3570	3574	3573	3575	3585	3579	3573	3573	3571	3576
2	3580	3578	3579	3581	3581	3582	3589	3585	3581	3581	3579	3583
3	3577	3576	3576	3579	3578	3580	3588	3584	3579	3579	3577	3581
4	3531	3525	3527	3536	3534	3540	3563	3550	3535	3535	3529	3541
5	3440	3427	3431	3452	3447	3462	3515	3485	3451	3450	3435	3465
6	3315	3292	3299	3337	3327	3354	3448	3395	3334	3332	3306	3359
7	3291	3267	3274	3315	3304	3333	3435	3378	3312	3310	3281	3339
8	3340	3319	3326	3360	3351	3376	3461	3413	3358	3355	3332	3380
9	3406	3390	3395	3421	3414	3432	3496	3460	3419	3417	3399	3436
10	3445	3432	3436	3456	3451	3466	3517	3488	3455	3454	3439	3468
11	3454	3442	3446	3465	3460	3474	3522	3495	3464	3462	3449	3476
12	3457	3446	3449	3468	3463	3477	3524	3497	3467	3466	3453	3479
13	3456	3444	3448	3467	3461	3475	3523	3496	3465	3464	3451	3478
14	3447	3434	3438	3458	3453	3467	3518	3489	3457	3456	3441	3470
15	3432	3418	3422	3444	3438	3455	3510	3479	3443	3442	3426	3457
16	3386	3369	3374	3402	3395	3415	3485	3446	3400	3399	3379	3419
17	3331	3309	3316	3351	3342	3368	3456	3406	3349	3347	3322	3372
18	3290	3265	3272	3313	3302	3332	3434	3377	3310	3308	3280	3337
19	3315	3292	3299	3336	3326	3354	3447	3395	3334	3332	3305	3358
20	3389	3372	3377	3405	3397	3417	3487	3448	3403	3401	3382	3421
21	3457	3445	3449	3468	3462	3476	3523	3497	3466	3465	3452	3479
22	3499	3491	3493	3507	3503	3513	3546	3527	3506	3505	3495	3514
23	3532	3526	3528	3537	3534	3541	3563	3551	3536	3536	3529	3542
24	3554	3551	3552	3558	3556	3561	3576	3567	3557	3557	3553	3561

Water draw duration

APPENDIX F SIMULATION VARIATIONS SUMMARY

Sim. Nr.	Sim. Type	Daily use profile	Hourly use profile	NOTE
1.1	BM	Yearly AVG 74.6 l/d – Adjusted for 10 apartments with applied MF	D	Placement of temperature senor for circulation on the return pipe, after circulation pump
1.2	BM	Yearly AVG 74.6 l/d – Adjusted for 10 apartments with applied MF	D	Placement of temperature senor for circulation on the return pipe, Before circulation pump
1.3	BM	Yearly AVG 74.6 l/d – Adjusted for 10 apartments with applied MF	D	Placement of temperature senor for circulation on the vertical supply branch, after heat exchanger.
1.4	BM	Yearly AVG 74.6 l/d – Adjusted for 10 apartments with applied MF	D	Supply pipe and circulation loop pipe are split in 5 parts of 8m each. Placement of temperature senor for circulation on the return pipe, after circulation pump
1.5	BM	Yearly AVG 74.6 l/d – Adjusted for 10 apartments with applied MF	D	Supply pipe and circulation loop pipe are split in 5 parts of 8m each. Placement of temperature senor for circulation on the pipe before connection point with circulation loop pipe.
1.6	BM	Yearly AVG 112 l/d – for single apartment, not adjusted	D	Water use for a single apartment. Temperature Set point for circulation activation 38°C
1.7	BM	Yearly AVG 112 l/d – for single apartment, not adjusted	D	Water use for a single apartment. Temperature Set point for circulation activation 45°C
1.8	BM	Yearly AVG 112 l/d – for single apartment, not adjusted	R	Water use for a single apartment. Temperature Set point for circulation activation 45°C
2.1	BM	Yearly AVG 74.6 l/d	D	Length of the circulation is 80 m ($L_{V.Branch}$+$L_{circ.\ loop}$). Distance to the tap 1m
2.2	BM	Yearly AVG 74.6 l/d	D	Length of the circulation is 70 m ($L_{V.Branch}$+$L_{circ.\ loop}$). Distance to the tap 11m
2.3	BM	Yearly AVG 74.6 l/d	D	Length of the circulation is 60 m ($L_{V.Branch}$+$L_{circ.\ loop}$). Distance to the tap 21m

3.1	ST	Yearly AVG 74.6 l/d	D	Placement of Temperature Sensor on the return pipe after the circulation pump
3.2	ST	Yearly AVG 74.6 l/d	D	Placement of Temperature Sensor on the return pipe before the circulation pump
3.3	ST	Yearly AVG 74.6 l/d	D	Placement of Temperature Sensor on the vertical supply branch after the storage tank
	BM – Benchmark ST- Storage Tank	L – Low M – Medium H - High	D – Danish research (adjusted) R – Random profile	

BIBLIOGRAPHY

[1] H. M. M. J. R. Saidur, »An application of energy andexergy analysis in residential sector of Malaysia, Energy Policy 35 (2) (2007).,« p. 1050–1063, 2007.

[2] T. Merrigan, »Residential hot water use in Florida and North Carolina,« 1988.

[3] »Suomen rakentamismääräyskokoelma osa D3, Rakennusten energiatehokkuus,Helsinki, Finland, 2012.,« 2012.

[4] »Building Regulations (Dannish), The Danish Ministry of Economic and BusinessAffairs, 2010.«.

[5] P. P. J. K. Kaiser Ahmeda, »Monthly domestic hot water profiles for energy calculation in Finnishapartment buildings«.

[6] M. M. B. Perlman, »Development of residential hot water use patterns,« 1985.

[7] E. D. R. S. R. Vine, »Domestic hot water consumption in four,« 1987.

[8] D. S. A. Abrams, »Effect of seasonal changes in use patterns and cold inlet water temperature on water-heating loads,« 1996.

[9] B. S. K. Becker, »Development of a hot water use data base,« 1990.

[10] M. R. M. L. K. Stokes, »A simple model of domestic lighting demand,« 2004.

[11] D. Parker, »Research highlights from a large scale residential monitoring study in a hot climate,« 2003.

[12] U. V. K. Jordan, »Influence of the DHW load profile on the fractional energy savings,« 2000.

[13] R. F. D. N. D. Spur, »Influence of the domestic hot-water daily drawoff profile on the performance of a hot-water store,« 2006.

[14] N. e. a. Enteria, »Case analysis of utilizing alternative energy sources and technologies for the single family detached house. Sol. Energy 105, 243–263.,« 2014.

[15] A. S. K. Hobbi, »Optimal design of a forced circulation solar water heating system for a residential unit in cold climate using TRNSYS. Sol. Energy,« 2009.

[16] J. P. R. T. V. Lima, »Optimization of tank and flat-plate collector of solar water heating system for single-family households to assure economic efficiency through the TRNSYS program,« 2006.

[17] S. Knudsen, »Consumers' influence on the thermal performance of small SDHW systems—theoretical investigations,« 2002.

[18] W. K. S. Buckles, »Analysis of solar domestic hot water heaters,« 1980.

[19] C. e. a. Hidalgo, »Domestic hot water consumption vs. solar thermal energy storage: the optimum size of the storage tank,« 2012.

[20] S. B. M. L. A. Edwards, »Representative hot water draw profiles at high temporal resolution for simulating the performance of solar thermal systems,« 2015.

[21] T. F. F. L. Z. Chow, »Potential application of a centralized solar water heating system for a high rise residential building in Hong Kong,« 2006.

[22] S. Kalogirou, »Long-term performance prediction of forced circulation solar domestic water heating system using artificial neural networks,« 2000.

[23] J. C. R. Sterling, »Feasibility analysis of an indirect heat pump assisted solar domestic hot water system,« 2012.

[24] D. T. A. K. A. Wolf, »A central solar domestic hot water system performance and economic analysis. Energy 5, 191–205,« 1980.

[25] P. P. J. K. Kaiser Ahmed, »Hourly consumption profiles of domestic hot water for different occupant groups in dwellings«.

[26] R. L. Jensen, J. Nørgaard, O. Daniels og R. O. Justesen, »Person- og forbrugsprofiler,« 2011.

[27] P. K. Olsen, C. H. Christiansen, M. Hofmeister, S. Svendsen og J.-E. Thorsen, »Guidelines for Low-Temperature District Heating,« [Online]. Available: http://www.danskfjernvarme.dk/~/media/danskfjernvarme/gronenergi/projekter/eudp-lavtemperatur%20fjv/guidelines%20for%20ltdh-final_rev1.pdf.

[28] W. H. Organization, »WHO press,« 2007. [Online]. Available: http://www.who.int/water_sanitation_health/emerging/legionella.pdf.

[29] P. P. J. K. Kaiser Ahmed, »Hourly Consumption profiles of domestic hot water for different occupant groups in dwellings,« 2016.

[30] A. Dyrelund, Ramboll, [Online]. Available: https://stateofgreen.com/files/download/299.

[31] O. Gudmundsson, M. Brand og J. E. Thorsen, *Utilization of return water in district heating networks,* DK-Nordborg: Danfoss District Heating Application Centre , 2014.

[32] K. Gerhardy, »Das DVGW-Arbeitsblatt W 551 und die 3-Liter-Regel,« [Online]. Available: https://www.dvgw.de/fileadmin/dvgw/wasser/gesundheit/1202gerhardy.pdf.

[33] M. Brand, »Heating and Domestic Hot Water Systems in Buildings Supplied by Low-Temperature District Heating,« DTU Civil Engineering Department, 2013.