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Analysis of Grey-water Heat Recovery System in Residential Buildings

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MASTER THESIS

for

Magnus Kleven

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Analysis of grey-water heat recovery system in residential buildings

Analyse av varmegjenvinning fra gråvannet i boligbygg

Background and objective

Grey water is the term given to household drainage water that comes from the bath tub, shower, wash basin and washing machine. Grey-water can provide heat at approximate temperature of 20-30°C on a continuous basis. With the grey-water a significant quantity of heat energy disappears into the drains each day. This grey-water heat can be recovered and reused for space heating purposes. Hence, this can decrease heat demand for space heating and hot tap water. In addition, recovering of the grey-water could reduce high variations in the heat demand in buildings. The heat from the grey-water is recovered with the help of a complex system of filters and heat exchangers. Application of the grey-water heat recovery may require modifications to the plumbing system. The grey-water heat recovery has been implemented in the process industry, and it is becoming interesting technology for buildings. This master thesis has aim to analyze potential and application of the grey-water heat recovery.

This project work is closely related to The Research Centre on Zero Emission Building at NTNU and SINTEF (FME ZEB) that has the vision to eliminate the greenhouse gas emissions caused by buildings. This national research centre will place Norway in the forefront with respect to research, innovation and implementation within the field of energy efficient zero-emission buildings.

The main objective of FME ZEB is to develop competitive products and solutions for existing and new buildings that will lead to market penetration of buildings that have zero emissions of greenhouse gases related to their production, operation and demolition. The Centre encompasses both residential and commercial buildings, as well as public buildings.

The following tasks are to be considered:

1. Estimate available heat amount in grey-water in residential buildings. This implies to estimate temperature level and grey-water amount coming from the relevant grey-water sources in residential buildings, like from shower, washing machine, and dishwasher.
2. Literature study on relevant technologies for the grey-water heat recovery. Analysis of the interaction between the plumbing system for grey-water and heat energy supply system in building.

3. Calculate and analyze energy performance of the grey-water heat recovery. Compare energy performance of the grey-water heat recovery to building heating energy demand. Calculation has to include design and operation cases.
4. Based on the results in Task 3, perform techno-economic analysis for the grey-water heat recovery system in residential buildings.

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Within 14 days of receiving the written text on the master thesis, the candidate shall submit a research plan for his project to the department.

When the thesis is evaluated, emphasis is put on processing of the results, and that they are presented in tabular and/or graphic form in a clear manner, and that they are analyzed carefully.

The thesis should be formulated as a research report with summary both in English and Norwegian, conclusion, literature references, table of contents etc. During the preparation of the text, the candidate should make an effort to produce a well-structured and easily readable report. In order to ease the evaluation of the thesis, it is important that the cross-references are correct. In the making of the report, strong emphasis should be placed on both a thorough discussion of the results and an orderly presentation.

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Pursuant to "Regulations concerning the supplementary provisions to the technology study program/Master of Science" at NTNU §20, the Department reserves the permission to utilize all the results and data for teaching and research purposes as well as in future publications.

The final report is to be submitted digitally in DAIM. An executive summary of the thesis including title, student's name, supervisor's name, year, department name, and NTNU's logo and name, shall be submitted to the department as a separate pdf file. Based on an agreement with the supervisor, the final report and other material and documents may be given to the supervisor in digital format.

Department of Energy and Process Engineering, 20. February 2012

Olav Bolland
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Preface

This report is written as an answer to the master thesis "Analysis of grey-water heat recovery system in residential buildings" in the spring 2012. The thesis was with the Department of Energy and Process Engineering at NTNU in Trondheim, Norway. It has been a part of the study "Energy and Environment" and has been written in the last semester of a five year study.

I would like to thank NTNU and all the professors for their desire and determination to educate and share knowledge with students and give the best possible education over e five year study at NTNU.

I would also like to thank Anita Osses for all her support and help during my studies.

Last but not least I would also like to thank my academic supervisor Natasa Djuric at NTNU for the skilled help and guidance regarding the thesis.

Magnus Kleven

Stud.Tech Magnus Hustad Kleven
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Abstract

Annual operating costs for buildings are a substantial cost in a lifetime. It is therefore of interest to try and reduce these costs. A large fraction of this cost today as the buildings become more and more energy efficient is the cost of hot tap water.

The study in this report looks into the potential for energy savings from grey wastewater. It is here looked at the amount of energy which can be recovered from hot water leaving the building and reused for pre heating of hot tap water and heating of building. The unit which would recover this energy is referred to as the grey-water heat recovery unit in this report.

A residential building with three floors where each floor has one washing machine, one shower and one dishwasher has been as the case building for the report. The total living area of the building is 450 m^2.

In the case building used in this report as much as 17.1 % of the total used energy goes to heating of hot tap water. By installing a heat recovery system which can recover some of the energy stored in the used hot water which leaves the building, this this could be reduced to 10.9 % of the total used energy according to simulations done in SIMIEN. There are also possibilities of using this energy for heating of the building as well as pre heating of hot tap water.

There are a few different solutions for implementing a grey-water heat recovery unit which could give different energy recovery between 2 716 kWh/year to 3 759 kWh/year. The best solution would be to connect the grey-water heat recovery unit to pre-heating of hot tap water, heating of the building as well as installing an accumulation tank to store recovered energy in. The most simple solution which would give the lowest amount of recovered energy would be to just connect the grey-water heat recovery unit to pre heating of hot tap water.

In this report two different simulation programs have been used, EnergyPlus and SIMIEN, to find what impact the energy reduction would have on the building and to see if the simulations would correspond to the theoretical estimates done in this report. The theoretical estimates based on equations for heat recovery and measured data for energy use in the case building gave a little bit better results than the simulated results for the same case building. Although

there is a difference both gave a positive indication that a heat recovery unit would not only reduce the energy consumption but also reduce the annual operating cost of a building.

The investment cost for a heat recovery system could be a bit large for small buildings compared to the annual savings but for larger buildings the investment cost could be substantially higher.

Regarding the energy as much as 87.7 % of the energy stored in the grey-water could be recovered for a system with an accumulation tank and a connection to the buildings heating system. For a system without the accumulation tank and district heating as the energy source it would have a theoretical efficiency of 76.7 % and a simulated efficiency of 63.3 % when simulated in EnergyPlus.

Sammendrag

Årlige driftskostnader for bygg er en stor kostnad når byggets levetid er tatt i betraktning. Det er derfor av interesse å prøve å redusere disse kostnadene. En stor andel av denne kostnaden i dag er varmt tappevann. Denne posten utgjør en større og større del av byggets kostnad ettersom byggene blir mer og mer energieffektive. Studiet i denne rapporten ser på potensialet for energisparing fra avløpsvann.

Det er her sett på mengden av energi som kan gjenvinnes fra varmtvann som forlater bygningen som kan gjenbrukes i forvarming av varmt tappevann og oppvarming av bygg. Enheten som brukes til å gjenvinne denne energien kalles en avløpsvannvarmegjenvinner.

Bolighuset som er brukt som eksempel i denne rapporten har tre etasjer hvor hver etasje har en vaskemaskin, en dusj og en oppvaskmaskin. Det totale boareal for bygningen er på 450 m^2. For bygningen som brukes i denne rapporten så går så mye som 17,1 % av den totalt brukte energien til oppvarming av varmt tappevann. Ved å installere et varmegjenvinningssystem som kan gjenvinne noe av energien som er lagret i avløpsvannet som forlater bygningen kan den totalt brukte energien for oppvarming av varmtvann reduseres til 10,9 % av den totalt brukte energien ifølge simuleringer gjort i SIMIEN. Det er også muligheter for å bruke denne energien til oppvarming av bygget, samt forvarming av varmt tappevann.

Det er noen forskjellige løsninger for å implementere en avløpsvannvarmegjenvinner som kan gi forskjellig mengde energigjenvinning fra 2 716 kWh/år til 3 759 kWh/år. Den beste løsningen vil være å koble avløpsvannvarmegjenvinneren til forvarming av varmt tappevann, oppvarming av bygningen, samt å installere en akkumuleringstank til å lagre den gjenvunne energien. Den enkleste løsningen som vil gi den minste energigjenvinningen vil være og bare koble avløpsvannvarmegjenvinneren til forvarming av varmt tappevann.

I denne rapporten er to forskjellige simuleringsprogrammer blitt brukt, EnergyPlus og SIMIEN, for å finne hvilken innvirkning energireduksjon ville ha på bygningen og for å se om simuleringene vil tilsvare de teoretiske beregninger gjort i denne rapporten. De teoretiske beregningene er basert på ligninger for varmegjenvinning og målte data for energibruk. De teoretiske beregningene ga et litt bedre resultatet enn de simulerte resultatene for samme

varmegjenvinningssystem i bygningen. Selv om det var en forskjell på simulering og de teoretiske beregningene så kom begge tilfellene ut med positive resultat. I begge tilfellene ville energiforbruket reduseres og ga indikasjoner på at det kan være økonomisk gunstig med et slikt system.

Investeringskostnaden for et slikt varmegjenvinningssystem kan være litt stor for små bygninger i forhold til de årlige besparelser, men for større bygg den investeringskostnaden kunne bli vesentlig høyere.

Når det gjelder energiforbruk så kan så mye som 87,7 % av energien som er lagret i avløpsvannet i for av varme gjenvinnes for et system med en akkumuleringstank og en forbindelse til bygninger varmesystemet i tillegg til forvarming av tappevann. For et system fjernvarme som energikilde, men uten akkumuleringstank vil den teoretisk beregnete virkningsgraden bli 76,7 % og den simulerte virkningsgraden bli 63,3 % når systemet er simulert i EnergyPlus.

Nomenclature

A_s	Heat transfer surface	[m^2]
B	Yearly economic savings	[NOK/year]
c	Capacity ratio	[-]
C	Heat capacity rate	[W/K]
C_{max}	Maximum heat capacity rate	[W/K]
C_{min}	Minimum heat capacity rate	[W/K]
c_p	Specific heat capacity	[kJ/kg*K]
E	Energy	[J]
I	Investment cost	[NOK]
m	Mass	[kg]
$\dot{m}$	Mass flow	[kg/s]
N	Economic lifetime	[years]
NTU	Number of heat transfer units	[-]
P	Power	[W]
Q	Heat transfer	[J]
$\dot{Q}$	Heat transfer rate	[W]
r	Interest rate	[-]
T	Temperature	[K]
T’	Pay-back time	[years]
V	Volume	[m^3]
$\dot{V}$	Volume flow	[m^3]
ΔT	Temperature difference	[K]
ΔT_{lm}	Logarithmic mean temperature difference	[K]

ε	Effectiveness	[-]
ρ	Density	[kg/m^3]

Subscripts

c	Cold
h	Hot
i	In
o	Out
s	Surface

Contents

Table List

Figure List

1 Introduction

1.1 Background

Grey-water is a term used to define water from showers, bath tubs, sinks, dishwashers and washing machines. The focus on recovering energy from grey-water has not been a priority when it comes to energy savings in buildings.

There are some solutions for heat recovery from drain water for showers (Shower-Save), and a solution for heat recovery from dishwashers (De Paepe, et al., 2002). These kinds of heat recovery systems demands single installations on the different water equipment, i.e. each water equipment needs its own heat recovery unit.

It could be more beneficial in the terms of the amount of energy recovered as well as economic to centralize the heat recovery. In this way more equipment could be connected to the same heat recovery unit and this opens more possibilities for use of the recovered energy. It could then be used for heating of the building as well as pre-heating of hot tap water. There are also possibilities to use different kind of heat pumps in connection with such a system (Fjellbu).

As buildings today are built to be more and more energy efficient and are using less and less energy. Heating of the hot tap water energy consumption becomes an extensible part of the total energy consumption in the building (Ulseth, 2010).

Unfortunately at this moment there are no rewards with this kind of system regarding the energy certificate, but there is a good possibility that the rules regarding the topic of heat recovery from grey-water could change in the future (Enova, 2012).

1.2 Goal

In this report it will be looked further in to how a centralized heat recovery system would reduce the amount of energy used for heating of water in buildings. The results will then be compared to solutions which already exist on the market regarding economic benefits and the amount of energy recovered.

It mainly focuses on small residential buildings but will also discuss the use of such a system in larger buildings. The report will try to find a solution to the question if a centralized grey-water heat recovery unit would give a positive economic benefit as well as a reduction in the used energy, and if this would be better than the solutions which exist today with single installations on water equipment? An example of grey-water heat recovery unit is illustrated in Figure 20.

1.3 Structure

In chapter 2 the theory for heat exchangers and existing solutions for heat recovery from showers and dishwashers are presented. The theory for the economic evaluations is also described in this chapter.

In chapter 3 the building used for simulations and calculations are introduced with all the important data before the energy in Norwegian households are described in chapter 4. This data is built on data collected for electricity use for different electrical equipment (Attachment 1: Measured Data).

Chapter 5 introduces different alternatives for implementations of a centralized system in buildings with different sources of energy.

In chapter 6 and 7 the results for energy saving for the case building explained in chapter 3 is found by theoretical estimations and simulations. These results are then used in chapter 8 to find the economic benefits for the different solutions.

At the end the results for economic and power savings for the different scenarios are summarized in chapter 9.

1.4 Limitations

Unfortunately the data collected is limited. There are no temperature measurements for the grey-water and the data is measured over a short time from 22nd of December until 26th of January. The data has been shortened down to 4th of January to 24th of January to avoid the Christmas time which would not be representable for rest of the year. The data is from one building with six occupants and for a very short time, so the data is not representable for a large amount of consumers. The data has been compared to other data as from the book "ENØK i bygninger" (Novakovic, et al., 2007), so it could be established if the data is reasonable.

The simulation program EnergyPlus has some limitations or very complicated construction when it comes to heat recovery from grey-water which again would feed an accumulation tank/boiler and therefore makes it hard to use the program for this specific simulation.

The simulation program SIMIEN does not take reduction in energy due to heat recovery from grey-water into consideration when it comes to the energy certificate. Therefore it can only be made assumptions on how this would affect the energy certificate since there are no guidelines for calculations of heat recovery from grey-water (Enova, 2012).

2 Theory

There is not a lot of theory based directly on a centralized grey-water heat recovery system. So in this chapter it is looked further in to theory for heat exchangers, heat recovery installations for showers which can be found on the market today, short about heat recovery for dishwashers, a little bit about washing machines and some theory about economic evaluations.

2.1 Heat Exchanger

This report will mainly focus on the shell and tube heat exchanger and the following equation and theory regarding chapter 2.1 is built on the books: Heat and Mass Transfer a practical approach (Cengel, 2006) and Fundamentals of heat exchanger design (Ramesh K, et al., 2003).

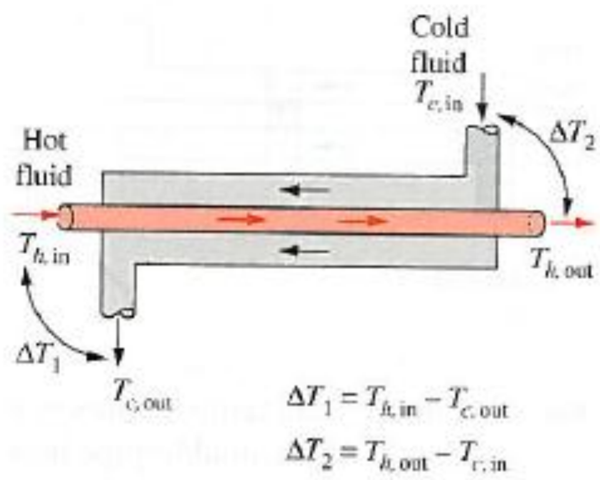


Figure 1: Counter Flow Heat Exchanger Sketch

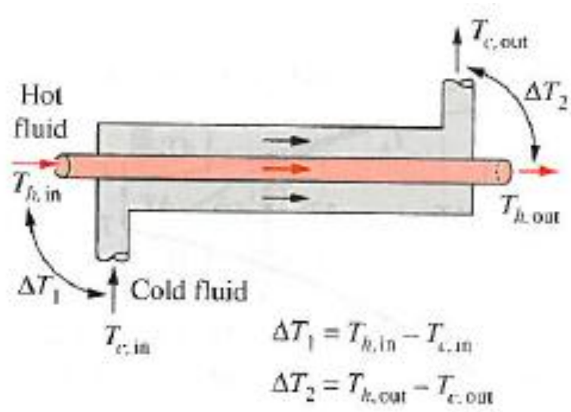


Figure 2: Parallel Flow Heat Exchanger Sketch

Equation 1: Power

$$P = \dot{m} * C_p * \Delta T$$

Equation 2: Mass flow

$$\dot{m} = \dot{V} * \rho$$

Equation 3: Total mass

$$m = V * \rho$$

Equation 4: Energy

$$E = m * c_p * \Delta T$$

Equation 5: Heat transfer with heat transfer coefficient

$$\dot{Q} = U * A_s * \Delta T_{lm} \text{ (Novakovic, et al., 2007)}$$

Equation 6: Logarithmic mean temperature difference

$$\Delta T_{lm} = \frac{\Delta T_1 - \Delta T_2}{\ln\left(\frac{\Delta T_1}{\Delta T_2}\right)}$$

Equation 7: Heat capacity rate for cold and hot fluid

$$C_c = \dot{m}_c c_{p,c} \quad \text{and} \quad C_h = \dot{m}_h c_{p,h}$$

Equation 8: Theoretical maximum heat transfer

$$\dot{Q}_{max} = C_{min}(T_{h,in} - T_{c,in})$$

C_{min} = the smallest of C_c and C_h.

Equation 9: Heat transfer for the cold side

$$\dot{Q} = C_c * (T_{c,o} - T_{c,i})$$

Equation 10: Heat transfer for hot side

$$\dot{Q} = C_h * (T_{h,i} - T_{h,o})$$

Heat transfer effectiveness ε based on the effectiveness NTU-method from 1955.

Equation 11: Heat transfer effectiveness

$$\varepsilon = \frac{\dot{Q}}{\dot{Q}_{max}}$$

The theoretical maximum heat transfer is built on assumptions as no leakage between the fluids, infinite transfer surface area and no heat loss to the surroundings (Ramesh K, et al., 2003).

Equation 12: Actual heat transfer

$$\dot{Q} = \varepsilon \dot{Q}_{max} = \varepsilon C_{min}(T_{h,in} - T_{c,in})$$

In order to be able to calculate the heat transfer rate ($\dot{Q}$) we would need to find the heat transfer effectiveness (ε).

Equation 13: Number of transfer units

$$NTU = \frac{U * A_s}{C_{min}} = \frac{U * A_s}{(\dot{m}c_p)_{min}}$$

For a double pipe parallel flow the heat transfer effectiveness would be as followed:

Equation 14: Parallel flow heat exchanger effectiveness

$$\varepsilon = \frac{1 - e^{-NTU(1+c)}}{1 + c}$$

$$NTU \frac{1}{c - 1} * \ln\left(\frac{\varepsilon - 1}{\varepsilon * c - 1}\right)$$

Where c = C_{min} / C_{max}.

For a double pipe counter flow:

Equation 15: Counter flow heat exchanger effectiveness

$$\varepsilon = \frac{1 - e^{-NTU(1-c)}}{1 - c * e^{-NTU(1-c)}}$$

In this report the focus will be on the double pipe counter flow exchanger.

2.2 Heat Recovery Shower Systems

Today there are several companies selling solutions for heat recovery from grey-water in showers. According to Shower-Save (Shower-Save) a modern working family could use as much as 90 % of all hot tap water for showering. More than 60 % of the energy going down the drain can be recovered by applying their product according to their home page.

Figure 3 illustrates an example of heat recovery in showers with a VX-pipe.

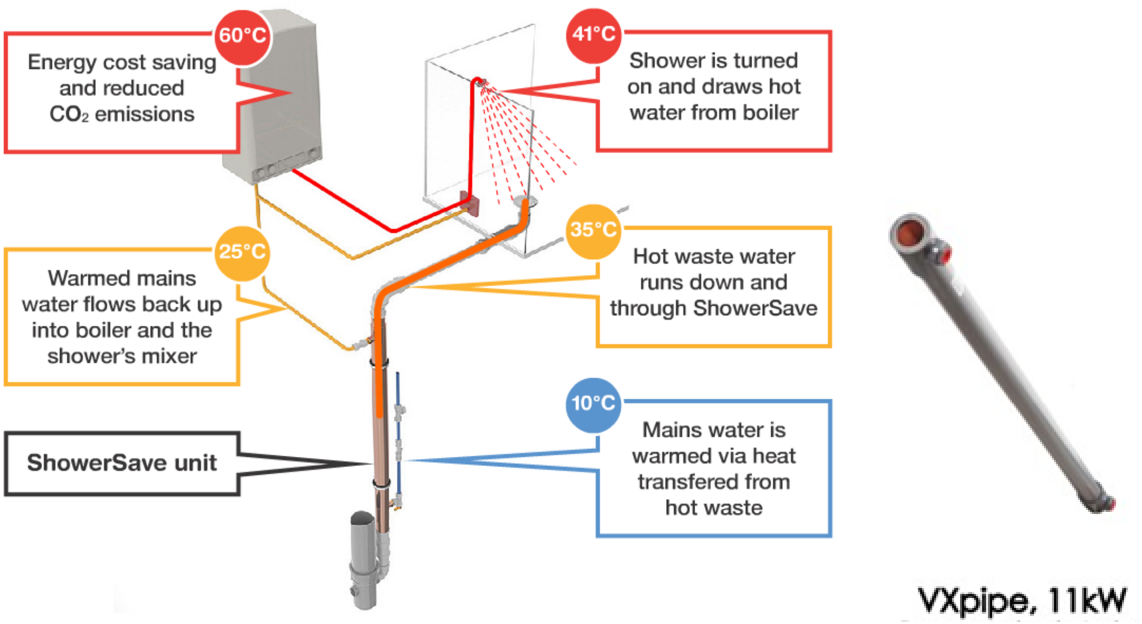


Figure 3: Shower recovery system sketch with a VX pipe (Shower-Save)

By using this particular example in Figure 3 where the temperature is lifted from 10 °C to 25 °C the total power produced from heat exchanger could be found by using Equation 1. Although there is an instantaneous water heater connected to the pipe after the heat recovery in Figure 3, this is not necessary. It can also be connected directly to the cold battery in the shower as shown in Figure 4.

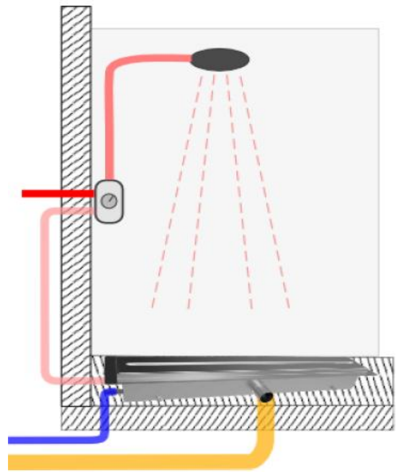


Figure 4: Connection to cold battery, here illustrated with a HXdrain (Meander)

By assuming a mass flow of 10.5 l/s (Watercycles, 2007) then the power produced would be 11 kW. This corresponds well to what Meander (Meander Heat Recovery) writes in their product manual about the exact same solution shown in Table 1.

Table 1: Performance of a VX-pipe

Flow rate (at 40 °C)	Shower drain water heat recovery unit efficiency and power delivered (at a cold water temperature of 10 °C)	Pressure drop
5.5 l/min	62.7 % (7.2kW)	< 20 kPa
7.5 l/min	59.3 % (9.3kW)	40 kPa
9.2 l/min	57.6 % (11.1kW)	55 kPa
12.5 l/min	56.0 % (14.6kW)	100 kPa

This gives an idea of how much heat which can be recovered from the grey-water.

The way heat recovery from the VX-pipe works is by forcing the water to swirl alongside the walls of the heat recovery pipe. This is done by letting the water build up speed from the drain until in enters the VX-pipe (Watercycles, 2007), the cold water then comes as a counter flow in a pipe swirled around the VX-pipe on the outside as shown in Figure 5.

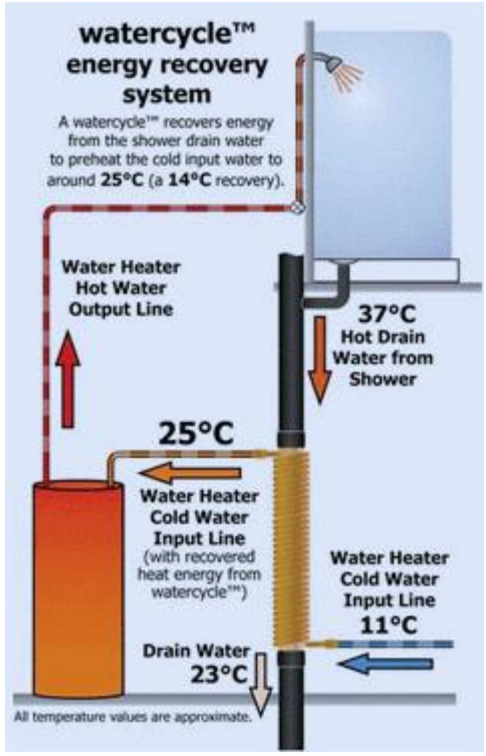


Figure 5: Installed VXDrain (Watercycles, 2007)

Another alternative which would not be as efficient would be the HeatSnagger for shower cabinets or the HX-drain for showers directly on the floor as shown in Figure 6. These installations don't require as much place but does not reach the same power and efficiency as the VX-pipe in Figure 3.

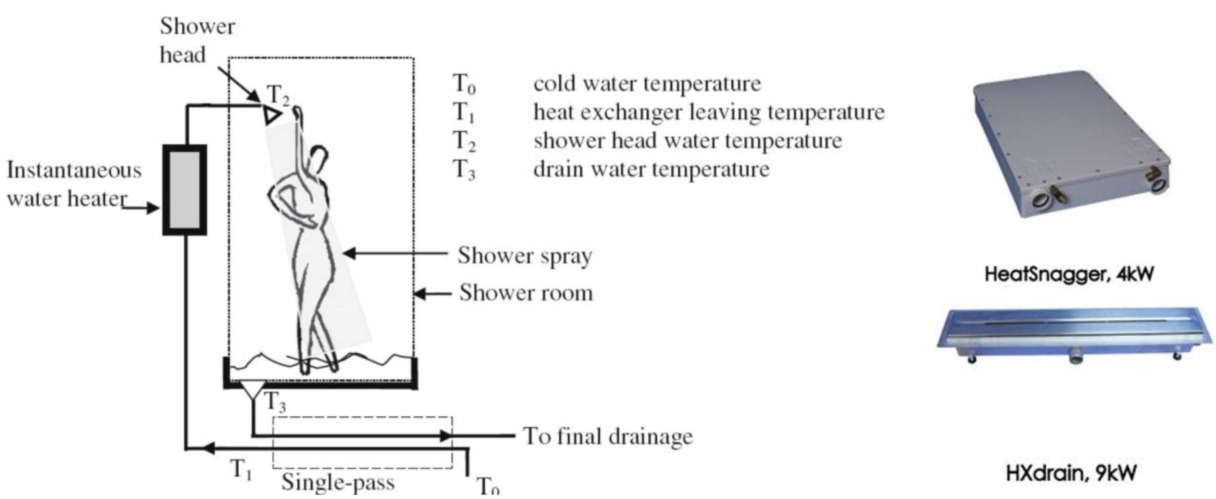


Figure 6: Sketch of shower and illustrations for heat recovery from HeatSnagger and HX-Drain

For the Heatsnagger the lift could be from 10 °C to 15.5°C and for the HXdrain it could be from 10 °C to 22 °C. This is based on the numbers from Shower-Save (Shower-Save) for power, and the assumption of a mass flow of 10.5 l/min which is used in Equation 1.

2.3 Heat Recovery Dishwasher

There is not a lot of research on this area. One of the reasons may be because of the low energy use for the dishwasher which would lead to small energy savings which can't justify the investment costs for a heat recovery system. This might be true in small residential buildings, but in places like hotels and restaurants the energy used for dishwashers can be quite substantial.

From the data collected from measured data the average use of energy for running the machine once would be 1,78 kWh (Attachment 1: Measured Data). The profile for power usage for the dishwasher based on the same data would be as shown in Figure 7:

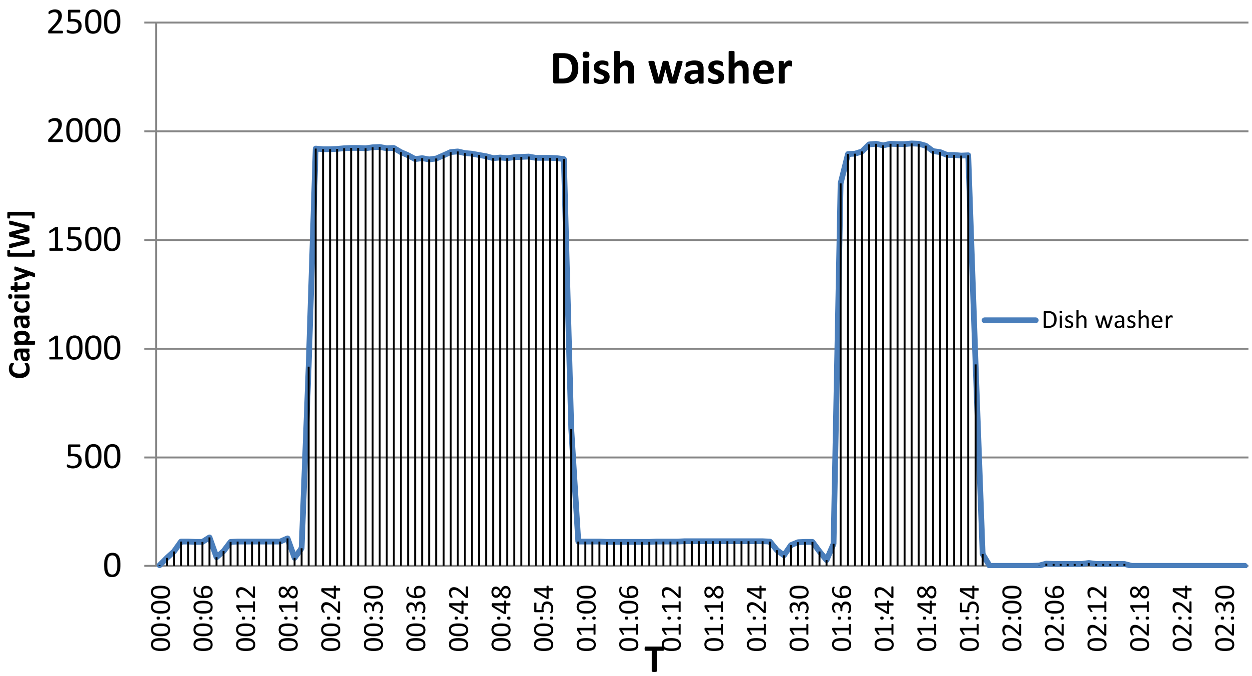


Figure 7: Washing Cycle for Dishwasher

Unfortunately this presents a dilemma when it comes to energy savings. There would not be any energy recovery in the first step if a system as shown in Figure 8 (De Paepe, et al., 2002) and Figure 9 would be installed. The reason for this would be that there has not been any hot water leaving the dishwasher at this moment. One way some heat can be supplied in the first step would be if the tank was very well insulated and there was some heat in the tank from last wash. If not the heat in the water leaving the dishwasher in the last cycle would most likely not be used back in to the machine.

One could argue with that the energy stored in the tank would then give an internal gain for the building rather than going down the drain.

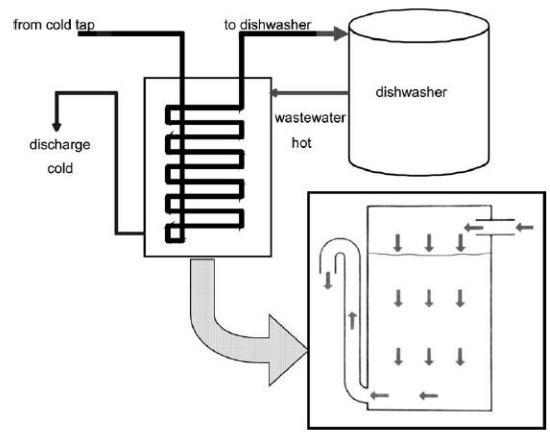


Figure 8: Heat Recovery System for Dishwasher

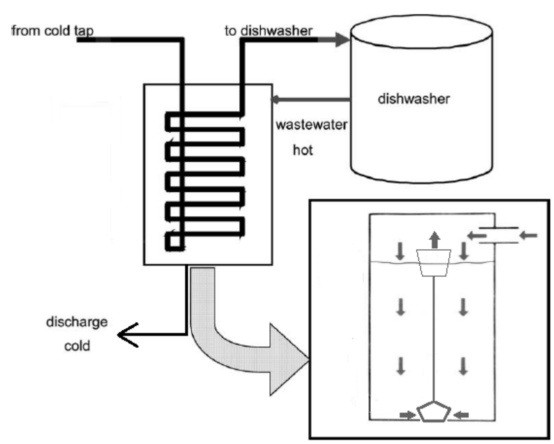


Figure 9: Heat Recovery System for Dishwasher Second Solution

Another alternative when it comes to washing cycle could be as shown in Figure 10 (De Paepe, et al., 2002). This is a very different washing cycle but is more likely to be more accurate since the data here was obtained by measuring the temperature from the water leaving the dishwasher rather than an estimate based on used electricity.

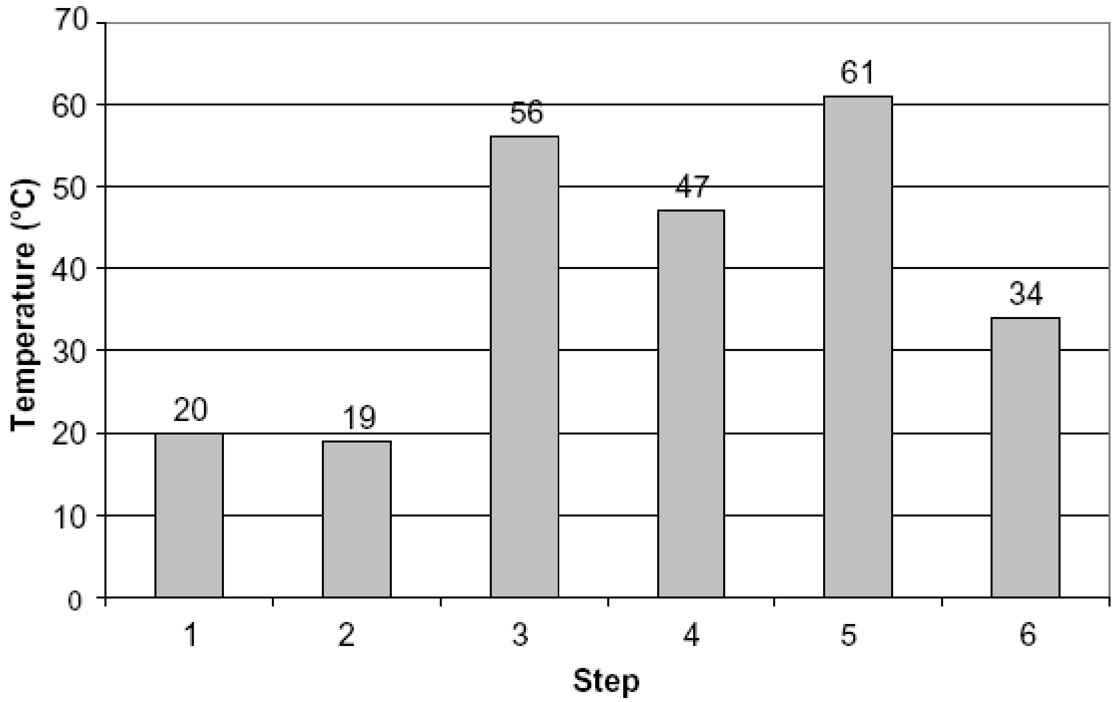


Figure 10: Alternative Washing Cycle for Dishwasher

It is the data from the first alternative (Figure 7 which is built on data from Attachment 1: Measured Data) that is mostly used in this report during simulations and calculations.

The dishwasher could prove to be a valuable source to the grey-water heat recovery unit since the temperature in dishwashers usually are in the area of 55 °C and above. Due to lack of data regarding temperature on wastewater from the single equipment, the temperature from the dishwasher has been assumed to be 55 °C for calculations and simulations done in this report.

2.4 Heat recovery Washing Machine

When it comes to heat recovery from washing machines, it is very hard to obtain any data or research done in this area. What could be obtained was data on energy consumption and amount of water used for one wash (LG, 2012) (BestBuy, 2012). These data has been compared to the average data from Attachment 1: Measured Data and is shown in Table 2.

Table 2: Energy and Water Consumption for Washing Machine

Model	Energy Consumption [kWh]	Water consumption [L]
LG	1,19	53
Samsung	1,02	48
Measured data	1,06	-

Unfortunately a washing machine has a lot of different programs which makes it hard to predict the temperature of the grey-water from the machine. The fact that the machine uses a large amount of water but not so much energy could indicate that it also use some cold water mixed into the washing process. This could be a problem regarding the grey-water heat recovery unit for heat exchanging and could be a reason for not connecting the washing machine.

By using Equation 4 we can see that from the measured data the amount of water which could be heated from 7 °C to 40 ° would be 27.5 liters. If the washing machine uses cold water at some stages, it would not be beneficial to let this water run through the grey-water storage unit.

To build a system so separate between cold and hot water in the drain leading from the washing machine could be an expensive solution. The conclusion here would be to exclude the washing machine from the grey-water heat recovery system. It is therefore done simulations, later in this report, with and without the washing machine to be able to see what energy could be saved if there were a reasonable solution to separate the hot and cold water in the drain.

From the measured data used in this report we can see that the washing cycle for washing machines can vary a lot as shown in Figure 11 and Figure 12.

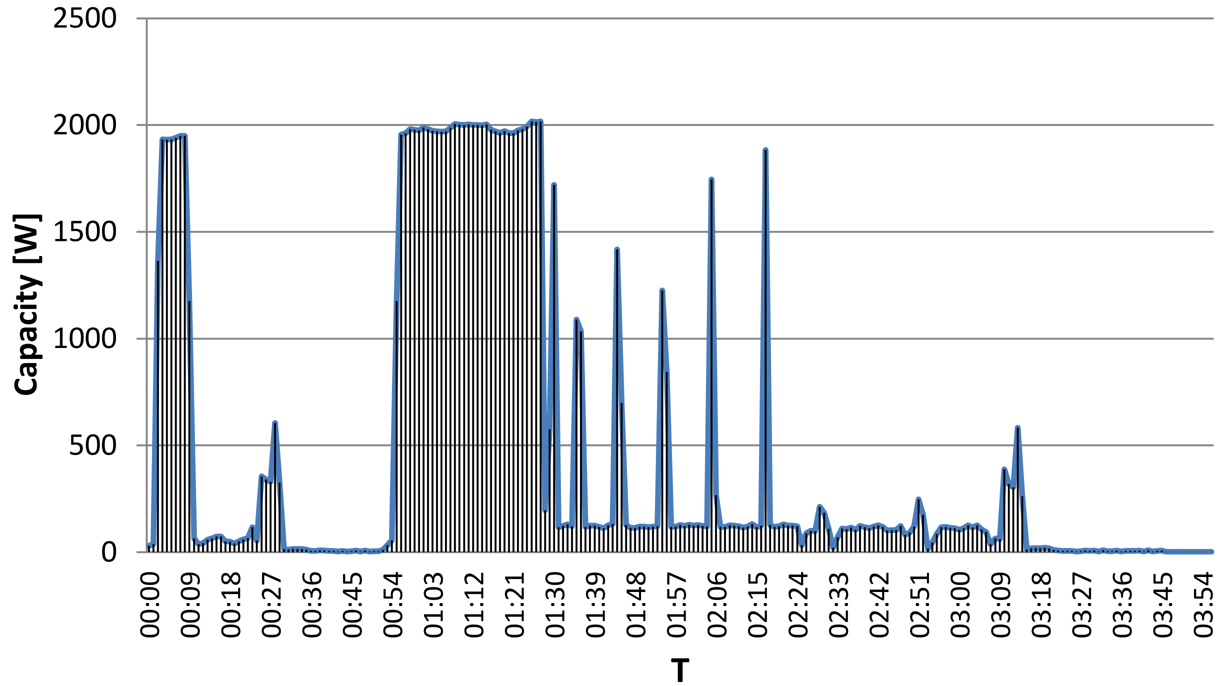


Figure 11: Washing Cycle. Alternative One for Washing Machine

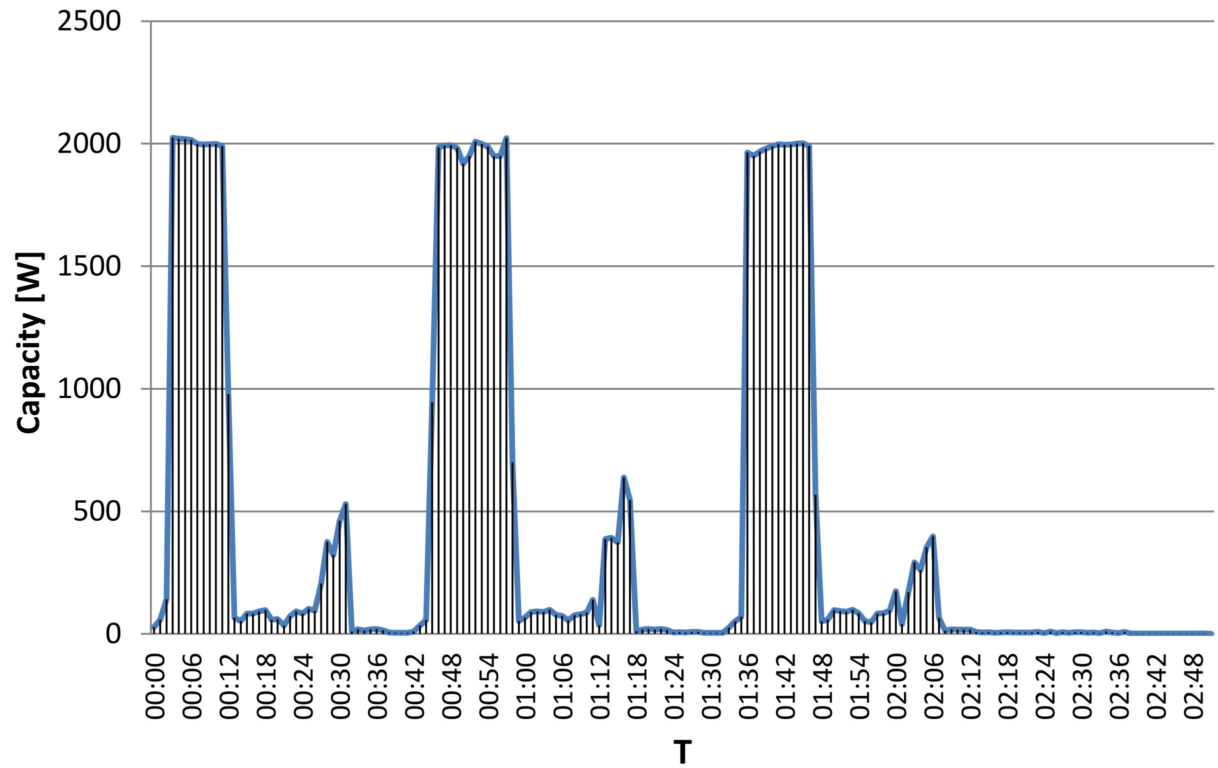


Figure 12: Washing Cycle. Alternative Two for Washing Machine

In the simulations done in this report, it is the alternative presented in Figure 11 which has been used when it comes to washing cycle program, and it is assumed that it is washing with 40 °C.

Another problem would be if the washing machine were running on temperatures up to 90 °C. This could give a temperature higher than the temperature which is wanted in such a system and could therefore require a security system to prevent too high temperatures at the water outlets.

2.5 Economic Analysis

When it comes to the economic benefits of installing grey-water heat recovery unit, there are several costs that needs to be taken into consideration. There are several different investment cost such as pumps, new piping in the building, regulators and valves in addition to the grey-water heat recovery unit which is illustrated in Figure 20.

The amount of money which could be saved with such a system also depends on the source of energy used for heating the hot water.

- **Investment cost**

The investment cost depends a lot on the system one chooses to install. If there should be a connection to the heating system as well as the hot tap water. This would probably be the main difference in the investment cost for the different systems illustrated in Figure 16, Figure 17, Figure 18 and Figure 19 in chapter 5.

- **Variable Costs**

The variable costs of such a system would be minimal. One of the benefits with using grey-water from the dishwasher as well as the other water equipment is that the chemicals from the dishwasher will help cleaning the heat exchanger. This would give a reduced demand for maintenance and therefore a reduced variable cost.

Other variable costs for such a system would be electricity to run pumps and regulation systems.

- **Required Rate of Return**

Before the decision for the investment can be taken, the required rate of return should be developed. The required rate of return builds on nominal interest i.e. loan interest in addition to a prospective risk (Brealey, et al., 2010).

The required rate of return should not give a negative outcome. The financial investment does not necessary have to be a loan, but it is necessary to still calculate how much it will cost to bind these financial funds and add a certain percentage for the risk and desired profitability.

- **Present Value**

The project will be beneficial in the eyes of the company if the value turns out to be positive. The interest rate (r) could include a company's demand of rate of return. In that way if the project comes out with a positive number in according to Equation 16 the investment fulfills the requirements from the company.

To be able to find the annual savings (B) the amount of energy and price for the energy source which would be reduced due by the recovery system should be obtained.

Equation 16: Present Value

$$NV = B * \frac{1-(1+r)^{-N}}{r} - I$$

- **Repayment Method**

The repayment method is also often known as the pay-back time.

It might also be interesting to find the time it takes for the investment to become beneficial. In order to find this it is necessary to see how long it takes for the savings to catch up to the investment. This can be found with the following formula:

Equation 17: Pay-back time

$$T' = \frac{\ln[(1-\frac{B}{B-I} * r)^{-1}]}{\ln(1+r)}$$

By using the required rate of return in the repayment method, the time is longer than in the actual case. In this report the interest rate which has been used are 6.5 %.

3 Case Building

In this report a building with three apartments on three different floors is used for the simulations done with SIMIEN and EnergyPlus later in this report.

Each floor has a total area of 150 m^2 with a 9 m^2 bathroom on each floor in the corner. Otherwise the walls are 10 x 15 and the building is built after the TEK 10 specifications.

The building is very simplified by not dividing the different floors into different rooms, but for this report this is not essential since it will not have a large impact on the results obtained for hot tap water use and for use of grey-water for heating of the building through heat radiant floors.

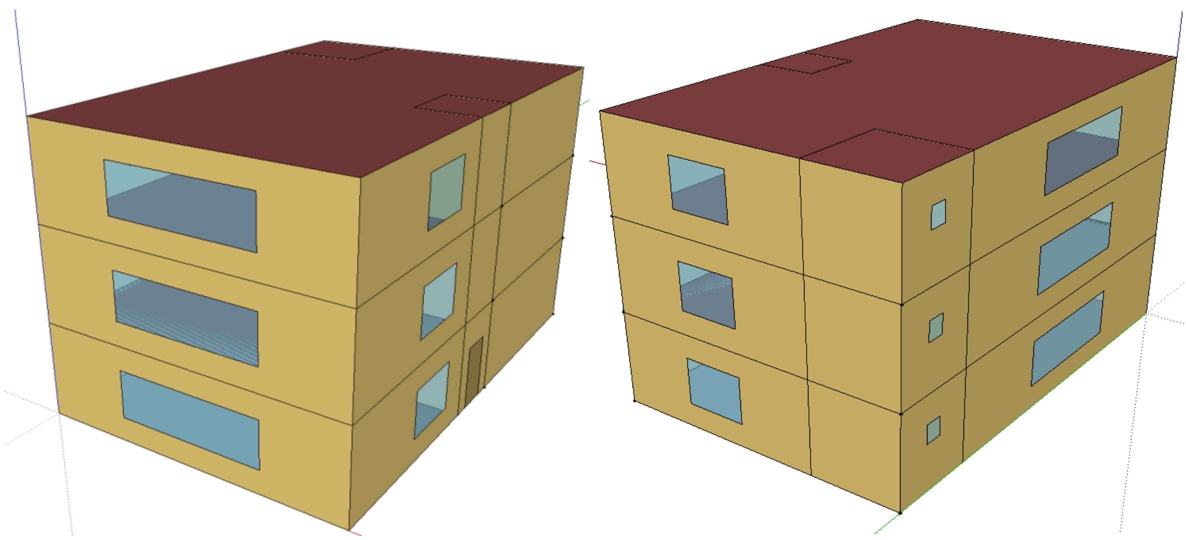


Figure 13: The building used for the simulations

In each floor of this building there are installed one shower, one washing machine and one dishwasher. There are also a total number of six persons on each floor (with background from the data: Attachment 1: Measured Data). The six persons on each floor is divided into different age groups and different patterns:

- Two persons less than six years old.
- One person between six and nineteen years old.
- Two persons between 20 and 40 years old.

- One person above 62 years old.
- One person stay-at-home.

The building is built on the following data obtained from a simulation in SIMIEN:

Table 3: Documentation of Essential Data from SIMIEN

Dokumentasjon av sentrale inndata (1)		
Beskrivelse	Verdi	Dokumentasjon
Areal yttervegger [m²]:	412	
Areal tak [m²]:	150	
Areal gulv [m²]:	150	
Areal vinduer og ytterdører [m²]:	56	
Oppvarmet bruksareal (BRA) [m²]:	450	
Oppvarmet luftvolum [m³]:	1353	
U-verdi yttervegger [W/m²K]	0,16	
U-verdi tak [W/m²K]	0,11	
U-verdi gulv [W/m²K]	0,12	
U-verdi vinduer og ytterdører [W/m²K]	1,02	
Areal vinduer og dører delt på bruksareal [%]	12,4	
Normalisert kuldebroverdi [W/m²K]:	0,06	
Normalisert varmekapasitet [Wh/m²K]	208	
Lekkasjetall (n50) [1/h]:	1,50	
Temperaturvirkningsgr. varmegjenvinner [%]:	84	

4 Energy Use for Norwegian Households

Today there are, as far as the author of this report knows, not so many measurements on data for hot tap water use in Norwegian households. The measurements used in the report are from electrical measurements done on a building with 300 m^2 living area and a total of six occupants. These numbers has been multiplied by three to make an estimate for the case building shown in chapter 3 and are shown in Table 4 and to obtain reasonable estimate for hot water usage.

Table 4: Total Hot Water Use in kWh

	Estimated pr. day [kWh]	20 days (amount of data available) [kWh]	Estimated for 1 year [kWh/year]	Average kWh used when equipment is on [kWh]	Estimated use for the case building [kWh/year]
Hot water boiler	9.57	191.49	3 494	1.52	10 484
Washing machine	0.80	15.96	291	1.06	874
Dishwasher	1.87	37.44	683	1.78	2 050
Total	12.24	244.88	4 469	4.37	13 407

By using distributions patterns obtained from “ENØK i bygninger” (Novakovic, et al., 2007) a certain estimate for consumed energy in the different water equipment could be obtained. It is also worth mentioning that the measured data for the hot water boiler at 3494.71 kWh pr. year corresponds very well to the assumed consumption of 3000 – 4000 kWh/year from “ENØK i bygninger” (Novakovic, et al., 2007).

According to “ENØK i bygninger” it is assumed that 60 % of the hot water is used in the bathroom. For the kitchen it is assumed 25 % and for wash basins a total of 15 % (Novakovic, et al., 2007). So to be able to calculate how much of the hot water boiler is used for showering, it was separated as shown in Table 5.

Table 5: Hot Water Boiler Distributions in kWh

	Estimated use pr. day [kWh]	Energy used in 20 days [kWh]	Setimated use for 1 year [kWh/year]	For 3 units [kWh/year]
Shower	5.17	103.41	1 887	5 661
Sink in Bathroom	3.45	68.94	1 258	3 774
Sink in kitchen	0.96	19.15	349	1 048

In these numbers it is also assumed by the author an apportionment of 90 % of hot water in the bathroom goes to showering. This number can be discussed if it should be less, but it is a lot less than the numbers Shower-Save presents as mentioned in chapter 2.2. There will also not be any heat recovery from the sinks and wash basins in this report. One of the reasons for this choice is because of larger particles from sinks and wash basins could contaminate the heat recovery unit and decrease the efficiency, or at worst case it could clod up the recovery unit to such an extent that it will stop working. Even without these water equipment connected, it is essential that there is a bypass system connected to the grey-water heat recovery unit. If not then in worst case if the grey-water heat recovery unit clods up it could lead to severe water damage in the building due to flooding.

The load profile for the building has been simplified and is shown in Figure 14. When the shower is on then it is on in all three apartments, the same for the washing machine and the dishwasher. By installing a grey-water heat recovery unit it is possibilities for reducing the load profile which could result in less required installed power in hot water boilers, or in a smaller heat exchanger for the district heating. Today there is usually a fee for installed power from the district heat companies which could be reduced by installing a heat recovery unit. These are bonuses which will be discussed further in chapter 10 Discussion.

Figure 14: Load Profile for Case Building Based on EnergyPlus Data

The hours which have been left out from the graph were periods during the day where the usage of energy for the three mentioned equipment in the graph were equal to zero.

The input used in EnergyPlus was based on the data from Attachment 1: Measured Data, and is fixed so the amount of energy would be the same although the time period the equipment's energy use is a lot less. This results in a very high heat transfer rate rather than a longer time period. This has been done so EnergyPlus would be able to calculate the water going down the drain rather than the energy used for heating the water in the washing machines and dishwashers.

In Figure 15 the heat transfer for the heating process in the water equipment is shown. The heat transfer here is significantly lower than in Figure 14 but the time it is on is a lot longer even though it is hard to see in this resolution.

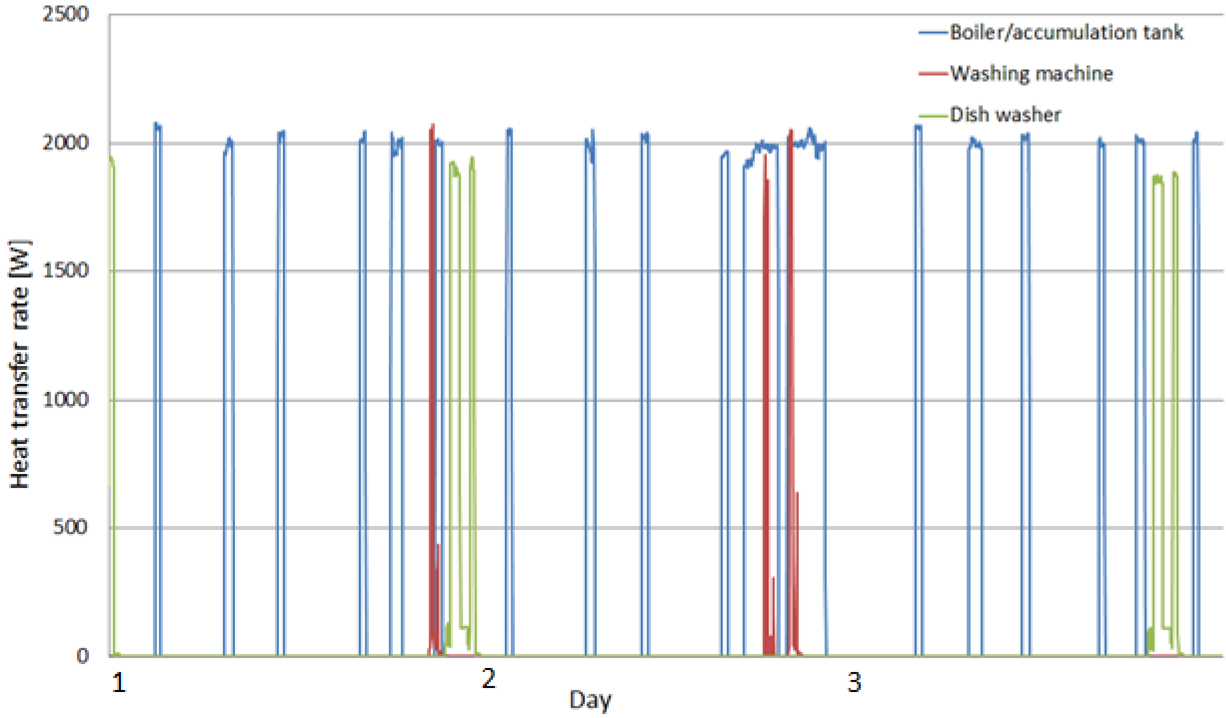


Figure 15: Load Profile from Attachment 1: Measured Data

Although the washing machine only uses 2000 watts to heat the water it is more important to look at the amount of water it uses and the energy which is in this water and how quick it will be emptied and refilled with water. It is the flow rate out of the machine which defines the amount of energy which goes through the grey-water heat recovery unit.

In Figure 15 it is the total energy used in the hot water boiler/accumulation tank and not the estimate on how much goes to the showers as in Figure 14. It is only illustrated four days to give an indication on use pattern for the different equipment. Figure 14 is built on an average use every day.

5 Alternative Implementations of a Grey-Water Heat Recovery Unit

There are different ways of implementing heat recovery from grey-water, but different solutions can give huge difference in efficiency as well as costs.

Regarding the washing machine, it will only be included in the first alternative (Figure 16).

5.1 Solutions with District Heating

By using recovery in combination with district heating there could be a conflict with the district heat companies. By preheating water entering the building there is a probability that the temperature difference between the feed line and the return line in the district heating net could become lower. This is an already existing problem in the district heating nets around Norway today (Jæger, 2011). This could be avoided if a solution for heat recovery from grey-water could be connected to the cold tap water line in a building on sources which did not need low temperatures. Some examples would be showers, dishwashers and washing machines. Regarding the washing machines it could be some complications. The temperature on the water entering the washing machine after using the grey-water heat recovery unit could be higher than the wanted temperature.

5.1.1 With Heating of Building and Pre-heating of Tap Water

The system in Figure 16 would be the most expensive system which is looked into in this report, but there are some advantages here that the other systems don't have.

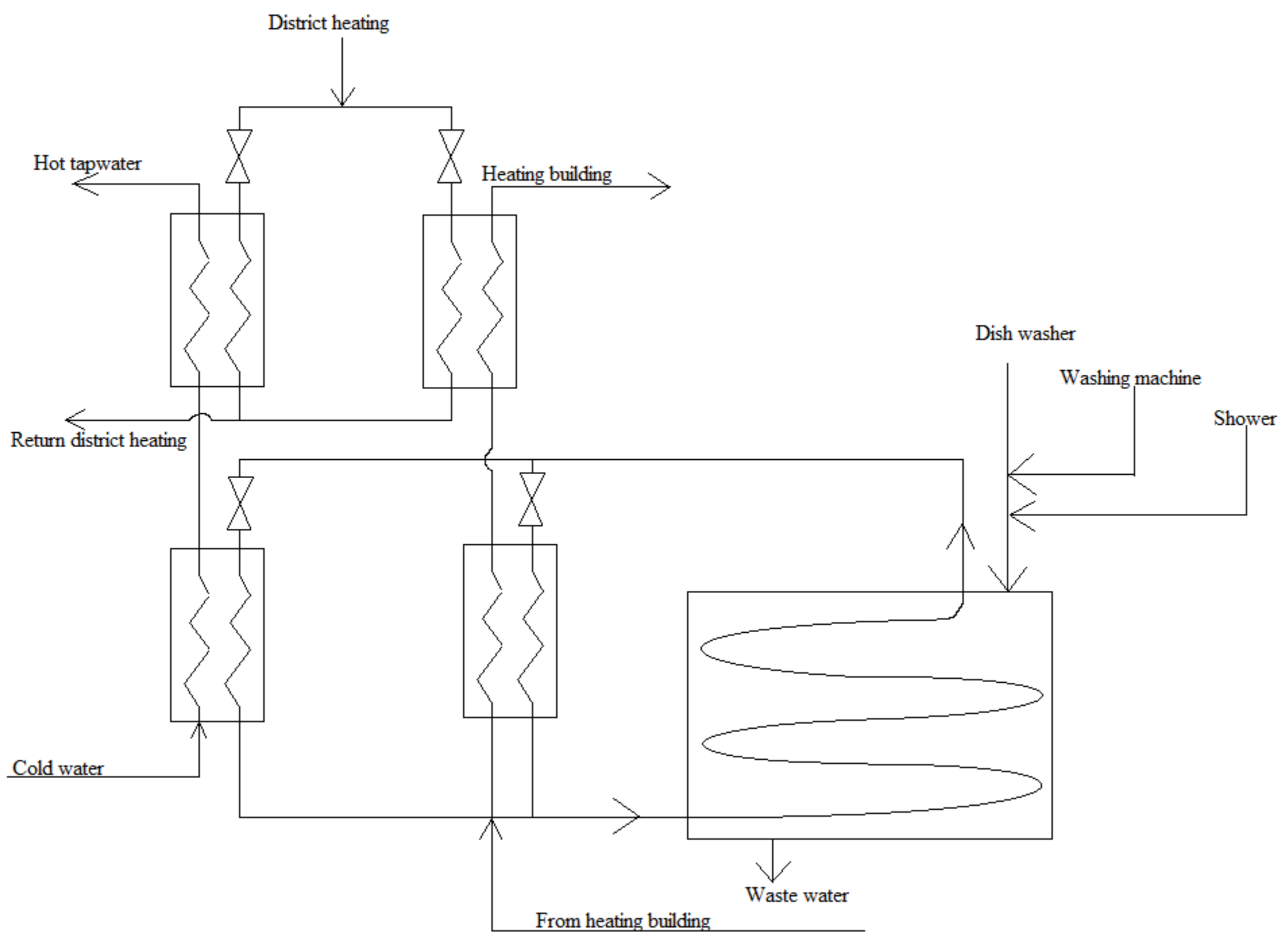


Figure 16: District Heating with Heating of Building and Pre Heating of Tap Water

By connecting the grey-water heat recovery unit to a low temperature heating system, such as floor heating, the recovered energy can be used for heating the building as well as tap water. This does set a requirement to the temperature of the grey-water. Even if the temperature of the grey-water is higher than the temperature coming back from heating of the building the efficiency would most likely be less for the heating of the building than for the tap water. This can be explained by the fact that the return temperature form the building would most likely be warmer than the cold water feed to the building which then again would give a smaller temperature difference.

Another minus with this kind of connection would be that the dishwasher and the washing machine will still be fed with cold water since there are no hot water connections for dishwashers and washing machines today. One solution to this would be to connect the machines to the pre heated water line, but this would make a huge impact on the investment costs of such a system and is not evaluated further in this report.

5.1.2 Only Pre-Heating of Tap Water

The system in Figure 17 would be a less expensive system since there are no connections between heating of the building and the recovery unit.

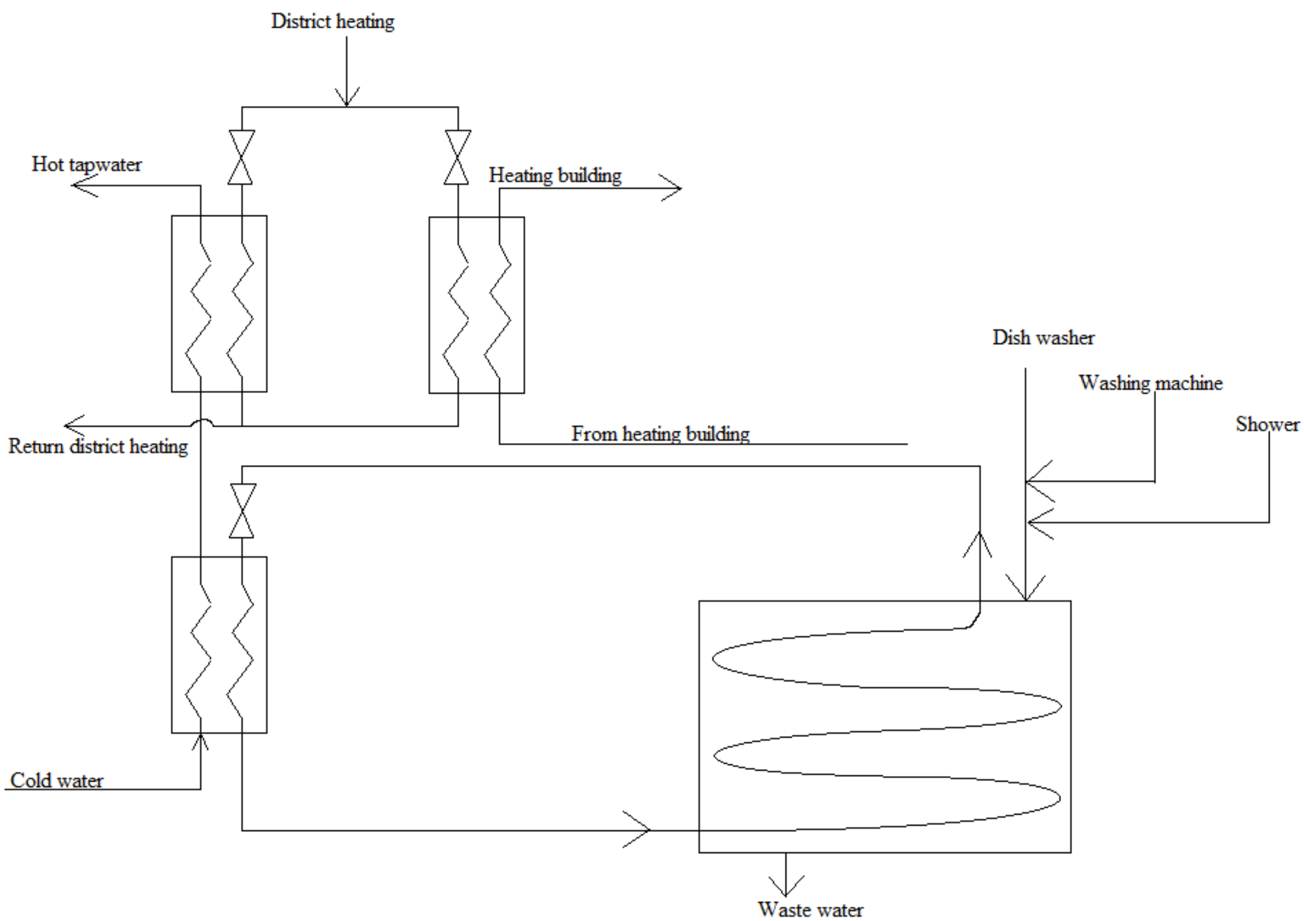


Figure 17: District Heating with Pre Heating of Tap Water

The negative side with a system like this is that when there is no use of hot tap water the grey-water in the grey-water tank will lose temperature to the surroundings.

5.2 Solutions with Hot Water Boiler

The trend today is a reduction in accumulation tanks around Norway due to the possibility for direct heat exchange between cold water inlet and the district heat inlet. But there are still a lot of these systems around in Norway, and a solution with heat recovery from grey-water could lead to reduced amount of resources for heating of water as well as reduced installed power in the tanks (Eslam-nejad, et al., 2009).

When there is an accumulation tank installed it gives an option to run the heat recovery system for a short time after the flow of hot tap water in the building reaches 0 l/s to fill the accumulation tank. This could give an increased efficiency of the heat recovery unit

5.2.1 With Heating of Building and Pre-Heating of Tap Water

The system in Figure 18 is almost the same as the one in Figure 16. The difference here is that the water enters a hot water boiler/accumulation tank before it is used in the building as hot tap water.

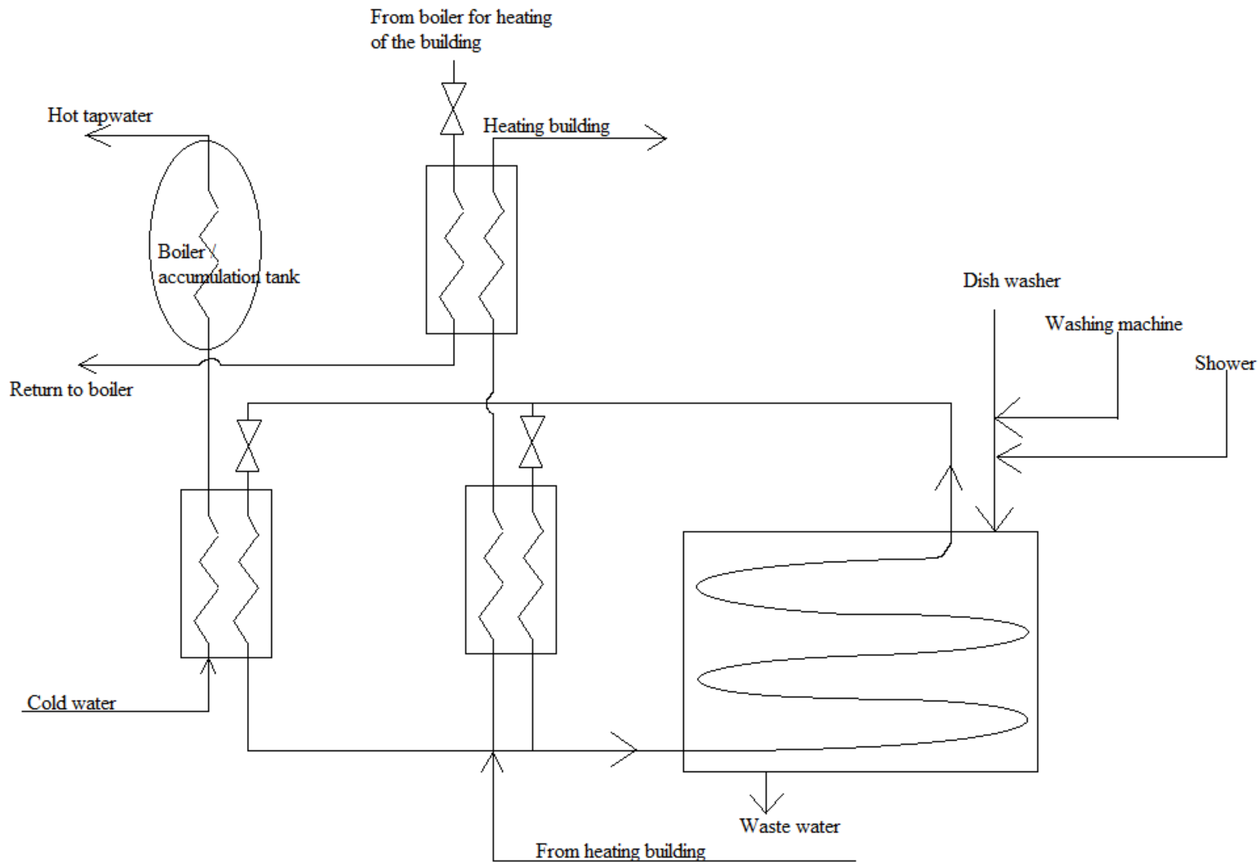


Figure 18: Pre-heating of Tap Water with Boiler and Heating of Building

One negative side with this is the extra investment cost for the hot water boiler. The hot water boiler would still be a necessity for the building if there are no alternative solutions with direct heat transfer for hot tap water.

One positive side would be the possibility to still run the grey-water heat recovery unit after the demand for hot tap water reaches 0 l/s in the building. This is due to the possibility to put in a delay on the hot water boiler. So the hot water boiler will be filled even after the demand stops. This would influence the necessity for the building heating connection. Since the heat recover can be used for filling the tank even after the demand ends, the heating system would not be as efficient as it is in Figure 16 where there is no storage for preheated water.

This system will not be prioritized in this report since the investment cost would be rather large for this system and the amount of energy recovered would not justify this solution rather than the one presented in Figure 19.

5.2.2 Only Pre-Heating of Tap Water

In Figure 19 the heating system for the building has been removed. This system would hypothetically almost have the same efficiency as the system in Figure 18 and will be prioritized in this report for further analyzes.

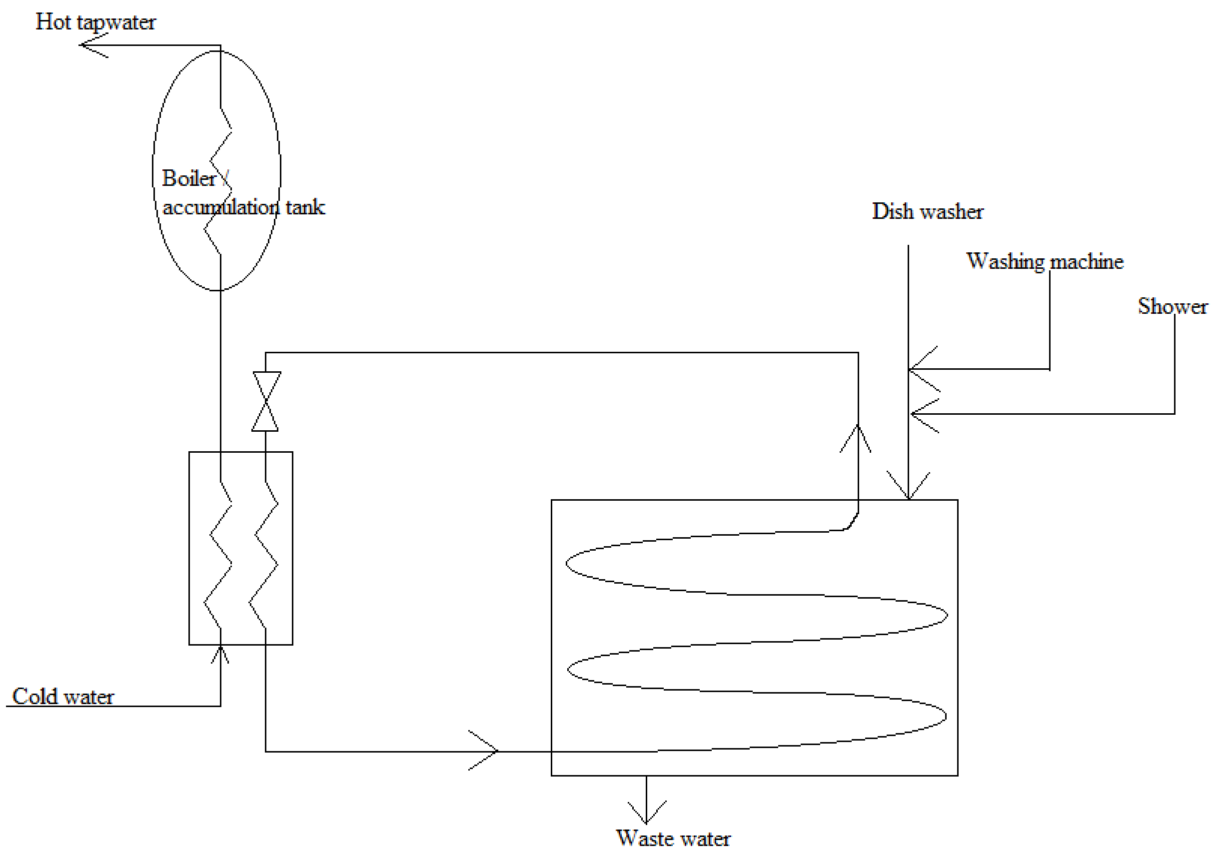


Figure 19: Pre-Heating of Tap Water with Boiler

This solution is not connected to the heating system of the building and has no connection to district heating. In Figure 19 the accumulation tank has an electrical coil to bring the temperature in the accumulation tank up to the desired level, which is recommended to be around 65 °C according to “Enøk Norge” if the accumulation tank is well isolated (Enoek Norge). It could be discussed if this temperature should be lowered if a system like this would be installed. The high temperature in the accumulation tank would give a low flow out when hot water is used which again would give little room for refilling the tank with water which has passed through the grey-water heat recovery unit.

6 Possibility of Energy Recovery from Grey-water

In this chapter there are done simple calculations to find the amount of energy, which in theory could be recovered from the different systems mentioned in chapter 5. There are also calculations done for heat recovery from showers using the three different installations mentioned in chapter 2.2.

There has also been made a simple estimate for the heat recovery system for dishwashers as mentioned in chapter 2.3.

6.1 Shower Systems

By assuming that the power for the different systems mentioned in chapter 2.2 is correct, the lift of temperature could be found from Equation 1 by using the mass flow 10.5 l/s from chapter 2.2.

The total amount of energy recovered over a year could then be found by using an estimate on total use of shower water during a year based on the data from Attachment 1: Measured Data. It is also assumed a constant temperature from the water supply to the building at a temperature of 7 °C and the average time pr. shower is four minutes.

The results for saved energy and the lift from 7 °C before the water enters the shower would then be as shown in Table 6.

Table 6: Energy Reduction per shower with Heat Exchanger

	Temperature after Heat Exchange [°C]	Energy used pr. shower without heat exchanger [kWh]	Energy used pr. shower with heat exchanger [kWh]	Percentage reduction in energy pr. shower [%]
HeatSnagger	12.4	1.715	1.448	15.6
HX-drain	26.2	1.715	1.115	35.0
VX-pipe	29.0	1.715	0.982	42.7

The result from Table 6 is used to find the total savings in one year. It is then assumed that there are three apartments with one shower each and each shower is used three times a day as an average. This would then give the following results presented in Table 7.

Table 7: Total Energy Reduction with Heat Exchanger for Shower

	Total energy used without heat exchanger [kWh/year]	Total energy used with heat Exchanger [kWh/year]	Total energy recovered pr. year [kWh/year]
HeatSnagger	5634	4757	877
HX-drain	5634	3663	1971
VX-pipe	5634	3226	2408

6.2 Dishwasher System

If the dishwasher system would be compared to the washing cycle which was shown in Figure 10, instead of the estimated washing cycle from Attachment 1: Measured Data, then the heat recovery would be significantly better. The estimated cycle is built on the use of electricity and could diverge from how the cycle is in reality regarding temperatures and water use.

Unfortunately the water inlet temperature in Norway is a lot lower than the water inlet temperature in Belgium at 20 °C which was used in a report about heat recovery from dishwashers (De Paepe, et al., 2002). Since the results in the report were built on measurements the results can't be directly transferred to the Norwegian conditions.

- **Washing cycle from Figure 10**

Here data from the report: Heat Recovery System for Dishwashers has been used (De Paepe, et al., 2002). A total of 5.5 l in every step and the temperatures as shown in Figure 10 has been used for the estimate. There will not be possibilities for any heat recovery before the dishwasher reaches step 4 since there is no hot water discharged from the machine before after step 3.

Due to the lack of data regarding design of the heat recovery system, it has been assumed that there would be a temperature difference between the cold water inlet and the grey-water outlet from the recovery tank of 20°C.

The amount of energy has been calculated out from the temperature data and scaled accordingly to the average use of 1.87 kWh pr. wash to be able to compare the influence of the washing cycle on the amount of recovered energy.

So by using Equation 4 with the mentioned data the total amount of recovered energy could be found and is displayed in Table 8.

- **Estimated washing cycle**

By using Equation 4 and the data obtained from Attachment 1: Measured Data for the average use of 1.78 kWh, which would be the same as 6 408 kJ pr. wash the amount of water could be found. This report has calculated with a target temperature in the dishwasher of 55 °C and the inlet temperature of 7 °C. This would then give a total hot water discharge from the machine (if calculated adiabatically) of 31.8 l.

As mentioned in the previous example, there will not be any heat recovery before some hot water has been discharged from the machine. In this case it is reasonable to believe that there is at least one emptying of the machine as well as one refill during the first step in Figure 7. Then there would be three steps in the washing cycle shown in Figure 7 with an equal amount of water in each. By doing these assumptions and calculations then the total heat recovery could be displayed in Table 8.

Table 8: Total Energy Reduction with Heat Exchanger for Dishwasher

	Total energy used without heat exchanger [kWh/year]	Total energy used with heat Exchanger [kWh/year]	Total energy recovered pr. year [kWh/year]
Washing cycle from Figure 10	2050	1052	998
Estimated washing cycle	2050	1652	398

From the results it is easy to see that for a single installation like this the washing cycle for the machine has a large influence on the outcome of energy savings.

The results in Table 8 are rough estimates to give an overview of the potential for energy savings.

6.3 Centralized Grey-water Heat Recovery

Figure 20 shows an example of a grey-water heat recovery unit which could be installed:

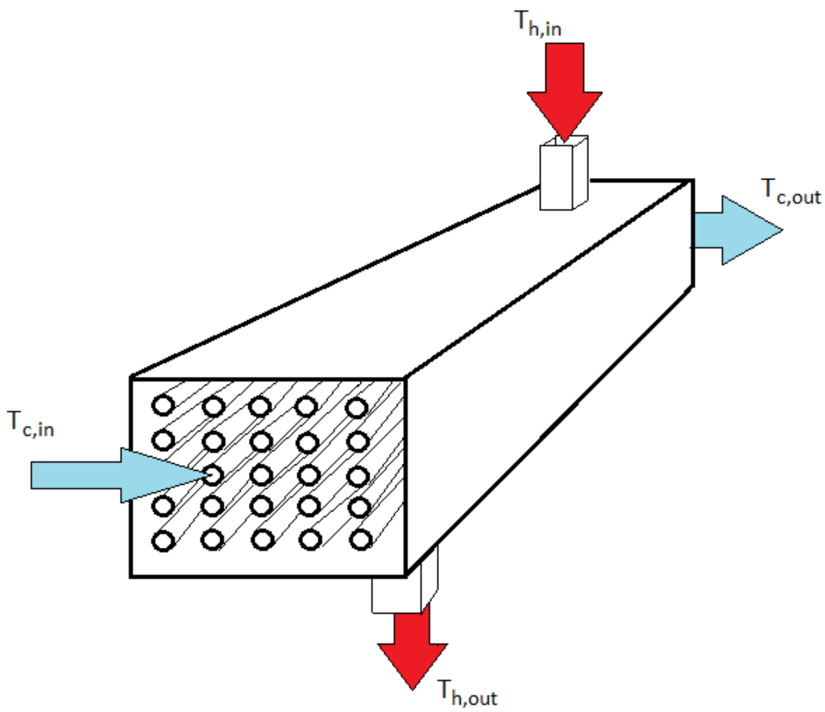


Figure 20: Example for Grey-water Heat Recovery Unit

If the length and width of the small sides would be approximately 22.4 cm and the depth 1 m with 25 tubes for cold water from the main supply line to the building, this would give a total storage of grey-water of 42.1 liters. This is if the small tubes would have a diameter equal to 2.5 cm.

By using Equation 5 and Equation 6 the overall heat transfer coefficient could be found to be 925 W/m^2K which is in the feasible area for a water to water heat exchanger which usually have an overall heat transfer coefficient of 850 – 1700 W/m^2K (Cengel, 2006).

This would give a heat exchange surface [A_s] of 1.57 m^2.

With this design the amount of water in the pipes would be approximately 6.4 liters.

In the centralized plant system, it is necessary to look at all the different water equipment by itself since the grey-water temperature varies in the different water equipment.

The grey-water flow entering the grey-water tank will be more than the cold water flow entering the grey-water tank. By using Equation 7 it can be proven that $\dot{m}c_{p,CW} < \dot{m}c_{p,GW}$ will for all the different water equipment would be true except for the dishwasher where $\dot{m}c_{p,CW} = \dot{m}c_{p,GW}$. When the dishwasher is mentioned here it is based on the argument that the water used in the dishwasher is the same as the temperature in the hot tap water line. It is also assumed that the dishwasher is connected to the hot water tap line which in reality is wrong.

By changing Equation 8 and set a fixed temperature difference between cold water out and the hot grey-water in for the grey-water heat recovery unit, it would be possible to make an estimate on the total energy saved. It is therefore assumed that the temperature difference for the designed heat exchanger between the cold side in and the hot side out will be a total of six degrees Celsius when designing it for the showers.

In Table 9 Equation 3 has been used to calculate the total amount of grey-water entering the grey-water tank. Unfortunately the specific density changes with temperature, but in this report it has been calculated to be a constant value of 1000 kg/m^3.

It is also estimated on the background of Attachment 1: Measured Data that the mass flow for the different equipment connected to the grey-water tank introduced in Table 9.

Table 9: Total Water Use

	Mass flow [kg/s]	Time used [min/day]	Total amount of water used [m^3/year]
Shower	0.525	12	137.970
Dishwasher	0,240	7	36.792
Washing Machine	0,198	7	21.621
Total	0,963	26	196.383

To be able to find the total amount of cold water flowing through the grey-water tank, which would be equal to the total amount of hot water at a temperature of 55 °C, Equation 1 has been used. Power on one side must be equal to the power on the other side (adiabatically). This would give the following results in Table 10

Table 10: Cold and Hot Water Use

	Cold water used [m^3/year]	Hot water used [m^3/year]	Energy used [kWh/year]
Shower	37.367	100.603	5661
Dishwasher	0	36.792	2050
Washing Machine	6.756	14.865	874
Total	44.123	152.260	8585

When it comes to the different systems shown in chapter 5, the amount of energy recovered could be very different from system to system. When there is no storage tank for hot tap water a system shown in Figure 16 would be able to recover more of the energy from wastewater than the system without heating of the building. The reason for this is the size of the heat recovery unit. Some of the grey-water would go down the drain unless the grey-water heat recovery unit can store enough water to cover the amount of water used in all the dish washers at the same time.

Another loss of energy would be the grey-water from the shower. When the showers turn off the water stored in the grey-water heat recovery unit can't be used for heating water to the dishwasher or washing machine since they are only connected to the cold water pipes in the building.

The system which could eliminate the loss off energy due to storage problem in the grey-water heat recovery unit would be the system with an accumulation tank.

Table 11 is an overview of advantages and disadvantages with the systems which were presented in chapter 5.

Table 11: Disadvantages with the Different Systems

	Loss due to limited storage	Loss due to no heating of building
Figure 16: District Heating with Heating of Building and Pre Heating of Tap Water	Yes	No
Figure 17: District Heating with Pre Heating of Tap Water	Yes	Yes
Figure 18: Pre-heating of Tap Water with Boiler and Heating	No	No
Figure 19: Pre-Heating of Tap Water with Boiler	No	Yes

The system with the lowest losses would be the one illustrated in Figure 18 but this would be the system which requires most space and has the highest investment cost.

In this chapter an estimate on unused heat recovery from grey-water is based on an estimate done from the data in Attachment 1: Measured Data and the simulated schedule for the use of the different water equipment in EnergyPlus. For the one which is done by calculations, estimates for different efficiency for the different systems mentioned in chapter 5 has been used.

6.3.1 Shower

In the first scenario we look at the solution for district heating with heating of building and tap water as shown in Figure 16.

The Heat exchanger is designed to have a temperature difference of six degrees Celsius for the shower flow. This would define the design of the heat exchanger, and is done since the shower is the main user of hot tap water in the residential building.

It is also assumed a temperature loss of five degrees Celsius from the shower head to the grey-water tank. This would give a shower temperature of 42 °C, which have been used for all shower calculations in this report, and a grey-water temperature of 37 °C which corresponds to the assumed temperature in Figure 5.

By using Equation 10 and Equation 8 the following results can be obtained as shown in Table 12:

Table 12: Energy Recovered from Shower in Centralized Grey-water Heat Recovery Unit

	Maximum heat transfer [kW]	Heat transfer [kW]	Energy recovered [kWh/year]
Shower ideal	16.08	12.86	2 817
Shower worst case	16.08	12.86	2 279

This would also give a temperature of 19.5 ° on the wastewater out from the grey-water heat recovery unit. This is unfortunately a very large temperature for the wastewater. One option to reduce this temperature could be to install a heat pump which exploits the wastewater from the grey-water heat recovery unit and use it for heating of the building or to lift the hot tap water up to desired temperature.

This result is also very ideal. There is not made any compensation for the delay between the water in the shower starts running and when the water temperature reaches desired level. When the shower is turned on the cold water will go down the drain and into the grey-water heat recovery unit, but this amount of water and the time it takes for the water exiting the shower head could almost be neglected.

When it comes to filling a bath tub, this scenario is not taken into consideration in the calculations in this report. If you fill a bath the only heat recovery that will be possible to gain is from the grey-water already stored in the grey-water heat recovery unit.

In the worst case scenario for the system in Figure 17 where there is only pre heating of tap water without a boiler the heat losses could be as much as 538 kWh pr. year. This is based on that once a day the shower water stored in the tank is flushed out without being used. This is not entirely true, but it is an estimate when you take the delay in startup for the heat recovery as well as the water in the tank after the shower stops for all the use of water in the shower. An example could be because of the dishwasher would replace the water in the tank. This would reduce the total energy recovered over a year to 2 279 kWh, as shown as worst case in Table 12.

If the system would have heating of the building then some of this energy could be recovered and used for heating of the building. This is also very dependent on the required heating for the building at that specific time.

6.3.2 Dishwasher

The dishwasher use the same temperature in the assumed washing program as the hot water supply. This will give a large temperature in the grey-water discharge from the machine. In this report it is assumed a temperature loss of 6 °C from the water heated in the washing machine enters the grey-water tank. The temperature in on the hot side for the grey-water heat recovery unit would then be 49 °C. By using the heat exchanger which was designed in chapter 6.3.1 the amount of energy recovered was calculated.

Table 13: Energy Recovered from Dishwasher in Centralized Grey-water Heat Recovery Unit

	Maximum heat transfer [kW]	Heat transfer [kW]	Energy recovered [kWh/year]
Dishwasher ideal	14.11	11.46	1 464
Dishwasher worst case	14.11	11.46	552

There is one small problem with the recovery from this equipment, and that is that a dishwasher usually has an internal heating coil for heating cold water which is fed to the machine from the cold water pipes in the building. So the water regained from the dishwasher is best equipped for heating of the building if there is no way to store the grey-water or there is no accumulation tank for the water which has been heated through the grey-water heat recovery unit.

With this particular grey-water heat recovery unit, the dimensioned storage capacity of 42.1 liters could be too small. Since one wash in dishwasher uses an average of 31 liters of hot water, it could be discussed if the grey-water heat recovery unit is too small when there are three dishwashers connected to the grey-water heat recovery unit, and as mentioned none of the heat will go back to any of the machines.

If this was the case, then an estimated amount of grey-water going down the drain without any heat recovery, for the case with heating of tap water but no heating of building, would be 51 liters. In that case it would be a total amount of 912 kWh which is about in worst case 62 % of the energy from the dishwasher entering the grey-water heat recovery unit. This is displayed as the worst case in Table 13.

If the grey-water should be used to heat the building, then it is floor heating which is best suited for such a solution due to the relatively low temperature compared to other heating sources in the building.

One advantage when it comes to connecting the dishwasher to the grey-water heat recovery unit is the reduced demand for maintenances in the unit. The strong washing chemicals used in dishwashers could take away the calcification which originates on the heat transfer area inside the unit. There are also strong chemicals made for cleaning the dishwasher which could have the same effect on the grey-water heat recovery unit.

6.3.3 Washing Machine

In this report it has been calculated with an average temperature in the washing machine at 40 °C. This would not be the same in real life. Some programs could be run with temperatures up to 90 °C and some at 30 °C. In cases with 90 °C there is a possibility that the temperature out from the grey-water heat recovery unit have a temperature higher than the wanted hot water temperature of 55 °C.

Another problem with connecting the washing machine to the grey-water heat recovery unit is the problem with hot and cold cycles in the washing machine. From the data on how much energy and water a washing machine uses (LG, 2012), it is impossible that all the water leaving the washing machine is hot water. This gives an indication that the washing machine might not be suited for the grey-water heat recovery unit unless there is a way to sort the cold and hot water leaving the washing machine. It is therefore in this report only made a calculation on what energy could have been saved if it would be possible to separate the cold and hot water.

Table 14: Energy Recovered from Washing Machine in Centralized Grey-water Heat Recovery Unit

	Maximum heat transfer [kW]	Heat transfer [kW]	Energy recovered [kWh/year]
Washing machine	5.46	5.22	475

From the results obtained from these calculations, the amount of energy absorbed in a washing machine is not a large amount of the used hot water energy out of the three different sources in this report. In fact the amount of energy used by the washing machine out of the total amount of energy is as little as 10.2 %.

6.3.4 Total Heat Recovery for the Grey-water Heat Recovery Unit

Until now it has been looked at the ideal system where the calculations have assumed that all water entering the grey-water heat recovery unit have been exploited. It is only for the dishwasher and the washing machine that the worst case scenario has been calculated. It is therefore looked further into the different solutions mentioned in chapter 5 in order to be able to make some rough estimates for an efficiency which could tell us how much of the grey-water can be used for heat recovery in the different systems.

To be able to make a good assessment of this efficiency more measured data would be necessary. The efficiency would depend a lot on the use pattern of the different equipment in the building so a mean efficiency could be found. In this report the measured data is only from one building and it has been multiplied with three to fit to the case building. This would give a coherent factor of water use in the different equipment of 1, i.e. when the shower in first floor is in use then all the showers are in use.

- **District Heating with Pre-heating of Hot Tap Water**

In this scenario there is a large chance for grey-water passing through the grey-water heat recovery unit without any heat exchange. By looking at the solution a bit pessimistic, then this system represents the worst case scenario as calculated above. In reality the efficiency would be a bit higher than the one represented in Table 15.

- **District Heating with Heating of building and Pre-heating of Hot Tap Water**

The fact that there is a system for heating of the building reduces the chance of grey-water passing through the heat recovery unit without exchanging any heat.

Water temperatures for a floor heating system could typically be between 30 and 36 °C. So by assuming the water temperature for the floor heating system returns at a temperature of 25 °C, an estimate for the energy used in this system could be made. It is also assumed that the system runs for 7 months since heating systems in building are usually turned off when the outdoor temperature is higher than 10 °C (Standard Norge, 2007). So by looking at the calculated energy which passes through the system without any heat exchange the amount of energy which could be used for heating of the building could be found.

From the shower where 538 kWh where lost (from chapter 6.3.1) the amount of heat recovered from this can be calculated by using Equation 5, Equation 4 and Equation 3 and multiply it with the time in use. This would give an increase in the recovery from shower by 62.8 kWh, and from dishwasher 390.9 kWh

The results are presented in Table 15.

- **Pre-Heating of Tap Water with Boiler**

If there is a delay to the refilling of the accumulation tank then all the water entering the grey-water heat recovery unit would have some grade of heat exchange with the water inlet to the accumulation tank. This would almost eliminate the losses from the grey-water from the showers passing through the grey-water heat recovery unit. The losses from shower water have therefore been neglected in this solution. For the dishwasher there would still be the same problem as before.

The results are presented in Table 15.

- **Pre heating of Tap Water with Boiler and Heating of Building**

In theory this should be the solution with the highest efficiency. Here losses for shower have been neglected as in the solution mentioned above. In addition to this the losses for dishwasher has been reduced as it was in the solution with district heating with heating of building and pre-heating of hot tap water.

The results are presented in Table 15 is without heat exchange from washing machine.

Table 15: Efficiency and heat recovery for the different systems

	Ideal Recovered Energy [kWh/year]	Assumed Recovered Energy [kWh/year]	Efficiency
District Heating with Pre-heating of Hot Tap Water	4 281	2 831	66.1 %
District Heating with Heating of building and Pre-heating of Hot Tap Water	4 281	3 285	76.7 %
El-boiler with Pre-Heating of Tap Water and accumulation tank	4 281	3 369	78.7 %
El-boiler with Pre heating of Tap Water, Heating of Building and accumulation tank	4 281	3 759	87.8 %

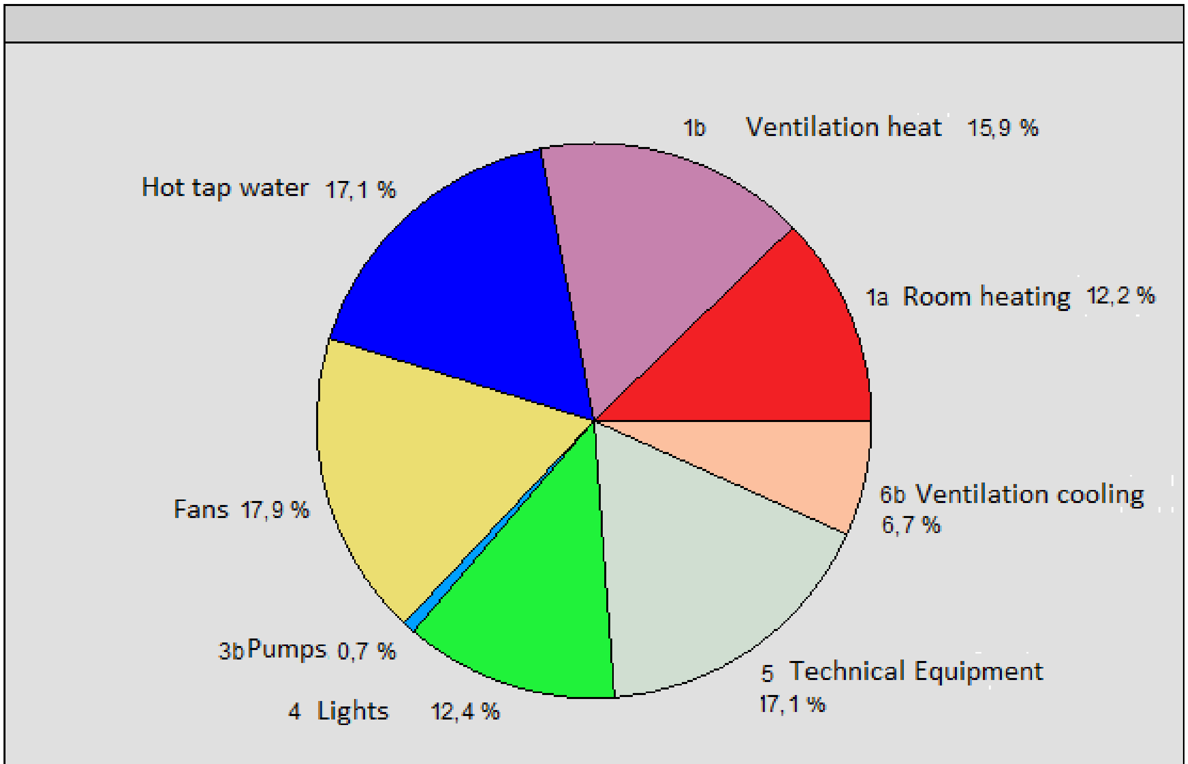
These results are very theoretical and are very dependent on use patterns in the building.

7 Simulations

In the simulations two different programs has been used. The first program is SIMIEN which is widely used in the Norwegian market today for energy making of buildings and further suggestions to different measurements which could be used to reduce the demand of energy. Unfortunately this program is not a very detailed program and does not have the opportunity to simulate heat recovery from grey-water. It is therefore also used a program named EnergyPlus. This program has a high level of details and also has the opportunity to simulate heat recovery from grey-water, but it is a complicated program and is not very user friendly.

7.1 SIMIEN

The simulations done in SIMIEN were mostly done to get an overview for the energy use in the case building and to see what kind of impact heat recovery from grey-water could have on the hot tap water as shown in Figure 21.



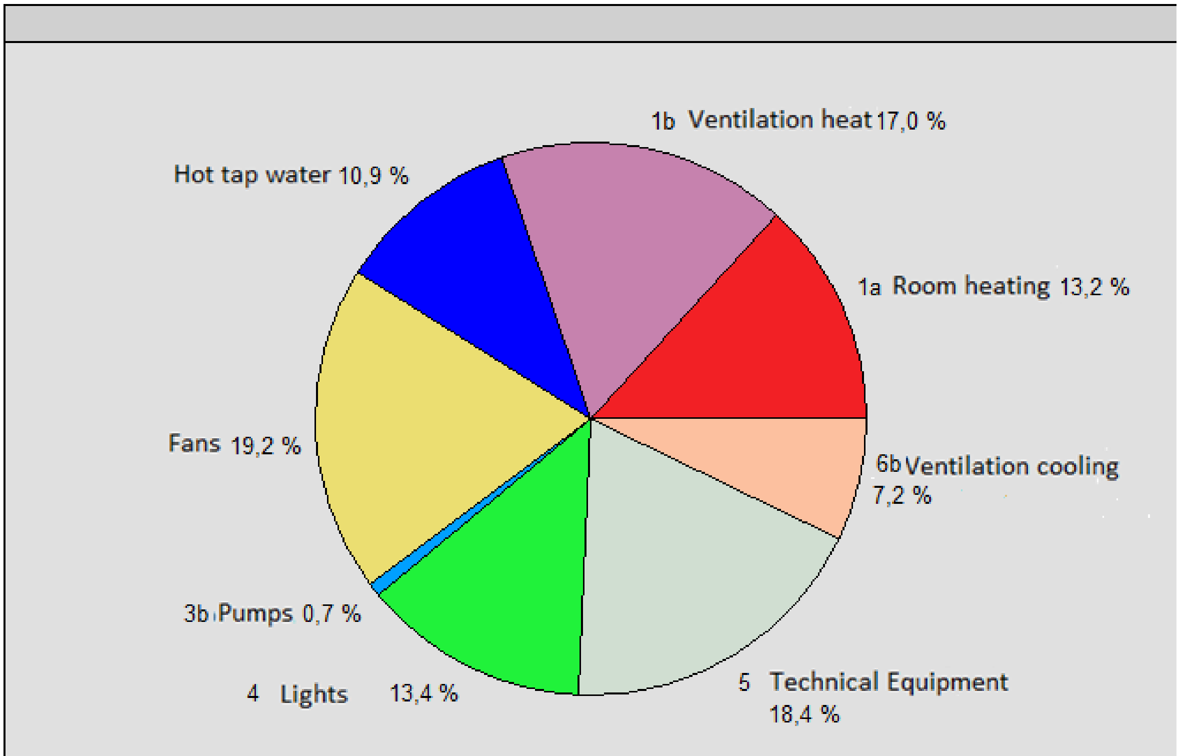
1a	Room heating	7515 kWh
1b	Ventilation heat	9724 kWh
2	Hot tap water	10486 kWh
3a	Fans	10951 kWh
3b	Pumps	417 kWh
4	Lights	7621 kWh
5	Technical equipment	10512 kWh
6a	Room cooling	0 kWh
6b	Ventilation cooling	4120 kWh
Total		61346 kWh

Figure 21: Overview of Energy Use

It is also worth mentioning that the total amount of energy used is 136.3 kWh/m^2.

In this simulation the energy use for dish washer and washing machine were implemented into the hot tap water use, it could be discussed if it should be in technical equipment since it uses electricity to heat the water. It is also worth mentioned that the measured data for hot tap water use is below the standard value for hot tap water at 5.1 W/m^2 (Standard Norge, 2007). According to this standard the total energy use for hot tap water would be 20 104 kWh which is far more than the measured data (Attachment 1: Measured Data).

By running the same simulations after subtracting the recovered energy from the estimates found in chapter 6, the results would be as shown in Figure 22 for a system without washing machine:



1a	Room heating	7515 kWh
1b	Ventilation heat	9724 kWh
2	Hot tap water	6210 kWh
3a	Fans	10951 kWh
3b	Pumps	417 kWh
4	Lights	7621 kWh
5	Technical equipment	10512 kWh
6a	Room cooling	0 kWh
6b	Ventilation cooling	4120 kWh
Total		57070 kWh

Figure 22: Energy Mark with Heat Recovery from Grey-water

In Figure 22 the fraction of hot tap water has been reduced from 17.1 % (Figure 23) to 10.9 % which is a total reduction of 6.2 % of the tap water and 4 276 kWh of the energy use which is approximately 7 % of the total energy use in the building. This is a significant number. It is also worth mentioning that the energy use went from 136.3 kWh/m^2 to 126.8 kWh/m^2.

When it comes to the energy certificate of this building, the result is shown in Figure 23:

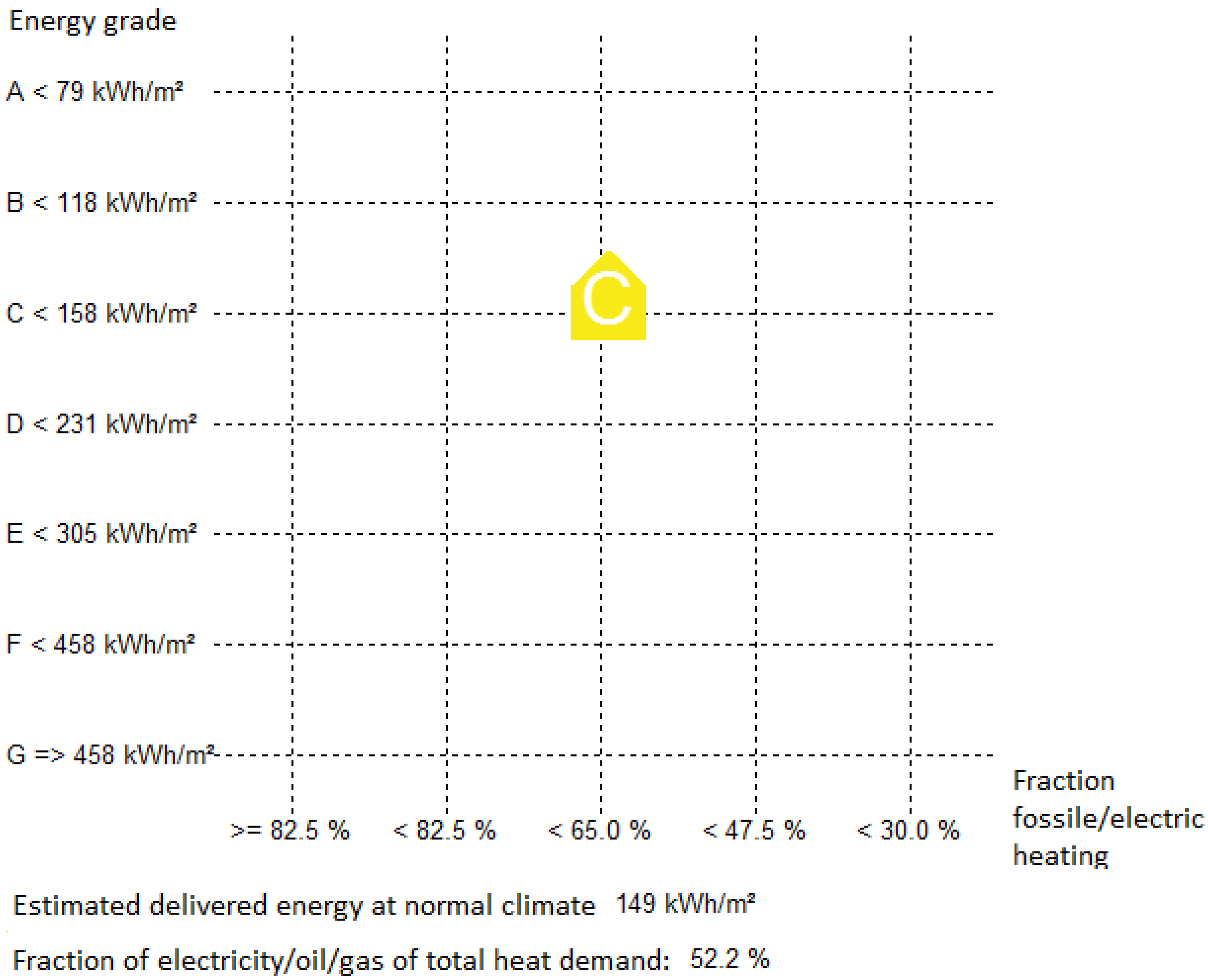


Figure 23: Energy Mark without Heat Recovery from Grey-water

The energy mark is divided into two different scales. On scale stretches from A to G and is a measurement of the total energy consumption pr. square meter and has system boundaries which look at energy in to the building and not from the source where the energy originated.

The other scale stretches from the color red which would be 100 % non-replaceable energy to the green color which indicates 100 % renewable energy. Here the building is shown with the color yellow. This is because the ventilation is run by an electrical heater. If the heating source for this heater would be changed to district heating the certificate would become green. Unfortunately the energy certificate is calculated on the background of standard values for hot tap water and will not change even though there are made changes to the hot water use. Today the grade of heat recovery doesn't have an impact on the energy certificate, and therefore it could be discussed if these rules should be changed so grey-water heat recovery would have an equal impact on the energy certificate as the ventilation.

7.2 EnergyPlus

In EnergyPlus four different simulations were done to be able to compare results.

The main energy contributor to the building is district heating and the four different scenarios are as followed:

1. Simulation for energy use with shower, washing machine and dishwasher
2. Simulation for energy use with shower and dishwasher
3. Simulation for energy use with shower, washing machine, dishwasher and grey-water heat recovery unit.
4. Simulation for energy use with shower, dishwasher and grey-water heat recovery unit.

The simulations done here is in accordance to the system shown in Figure 17. The reason it is most focus on this system is because of the possibility that it might not be economical beneficial to install a grey-water heat recovery unit in small buildings. It also requires a different solution for piping in the building than it is today to be able to separate shower and dishwasher wastewater from the rest of the wastewater. It is therefore more likely to be implemented in new buildings like large apartment buildings, hotels, gymnasium buildings and other buildings with a large hot water usage.

The input data for the water equipment and usage were collected from the measured data (Attachment 1: Measured Data).

The water temperatures used for the different equipment is an educated assumption.

7.2.1 Simulation with Shower Dishwasher and Washing Machine

This simulation was done so the comparison between the scenario with and without the washing machine could be compared.

Table 16 displays the results from the simulation in EnergyPlus and shows the kWh/m^2 as well as the total energy use for one year:

Table 16: Site and Source Energy for System with Washing Machine

	Total Energy [kWh/year]	Energy Per Total Building Area [kWh/m^2]	Energy Per Conditioned Building Area [kWh/m^2]
Total Site Energy	73 113	162.47	166.93
Net Site Energy	73 113	162.47	166.93
Total Source Energy	260 424	578.72	594.57
Net Source Energy	260 424	578.72	594.57

In this case the house would get an energy certificate equal to grade D compared to the guidelines in Figure 23 (Standard Norge, 2007).

The result deviates from the simulation done in SIMIEN and is most likely a deviation due to different level of details in the two simulations. In SIMIEN the energy use was 136.3 kWh/m^2 compared to a 166.5 kWh/m^2 in EnergyPlus and that is even when the water used in the sinks and other sources which has been excluded from the heat recovery unit has been removed from the hot tap water use.

Table 17 shows the input data for hot tap water use used in the EnergyPlus simulations.

Table 17: Simulated Energy Use with Washing Machine

	[MJ/year]	[kWh/year]
Shower	20 185	5 607
Dishwasher	7 382	2 051
Washing machine	2 994	832
Total	30 561	8 489

7.2.2 ***Simulation with Shower, Dishwasher, Washing Machine and Heat Recovery Unit***

The simplifications done in EnergyPlus, such as there are no cold water leaving the equipment and that all equipment is connected to hot water pipes in the building. Without these assumptions the simulations were not feasible.

Table 18 displays the results from the simulation in EnergyPlus and shows the kWh/m^2 as well as the total energy use for one year:

Table 18: Site and Source Energy for System with Washing Machine and Heat Recovery

	Total Energy [kWh/year]	Energy Per Total Building Area [kWh/m^2]	Energy Per Conditioned Building Area [kWh/m^2]
Total Site Energy	70 082	155.74	160.01
Net Site Energy	70 082	155.74	160.01
Total Source Energy	249 472	554.38	569.57
Net Source Energy	249 472	554.38	569.57

In Table 18 the kWh/m^2 has been reduced compared to Table 16. Unfortunately heat recovery from grey-water is not taken into consideration in the Norwegian standard for energy certification (Standard Norge, 2007). The Norwegian standards are still under development and it is very likely that this would be taken into consideration in the future (Enova, 2012).

Table 19 shows the simulated energy used for showers, washing machines and dishwashers.

Table 19: Simulated Energy Use with Washing Machine and Heat Recovery

	[MJ/year]	[kWh/year]
Shower	14 742	4 095
Dishwasher	3 048	847
Washing machine	1 867	518
Total	19 657	5 460

The total amount of energy saved with this system could be found by subtracting Table 19 from Table 17. The result would then be 3 029 kWh which is in between the calculated maximum of energy recovery and the worst case scenario calculated in chapter 6.3.

7.2.3 Simulations with Showers and Dishwashers

This simulation is the most accurate since the washing machine has been excluded from the system and the problem with cold water from the washing machine entering the grey-water heat recover unit has been eliminated.

Table 20 displays the results from the simulation in EnergyPlus and shows the kWh/m^2 which is uses as well as the total energy use for one year:

Table 20: Site and Source Energy for System without Washing Machine

	Total Energy [kWh/year]	Energy Per Total Building Area [kWh/m^2]	Energy Per Conditioned Building Area [kWh/m^2]
Total Site Energy	72 282	160.63	165.03
Net Site Energy	72 282	160.63	165.03
Total Source Energy	257 419	572.04	587.71
Net Source Energy	257 419	572.04	587.71

By comparing Table 16 with Table 21, where the energy use in the washing machine has been eliminated, the reduction in kWh/m^2 would be less than 2 kWh. This is an indication which shows that the impact from heat recovery from the washing machine would almost not have any impact on the energy certificate when or if this becomes of any interest.

Table 21 shows the energy use for hot water for the showers and dishwashers.

Table 21: Simulated Energy Use without Washing Machine

	[MJ/year]	[kWh/year]
Shower	20185	5607
Dishwasher	7382	2051
Total	27567	7657

7.2.4 Simulations with Shower, Dishwasher and Heat Recovery

This is the most realistic simulation since the washing machine which could have a negative impact on the system has been eliminated.

Table 22 displays the results from the simulation in EnergyPlus and shows the kWh/m^2 used as well as the total energy use for one year:

Table 22: Site and Source Energy for System without Washing Machine but with Heat Recovery

	Total Energy [kWh/year]	Energy Per Total Building Area [kWh/m^2]	Energy Per Conditioned Building Area [kWh/m^2]
Total Site Energy	69 563	154.58	158.82
Net Site Energy	69 563	154.58	158.82
Total Source Energy	247 596	550.21	565.29
Net Source Energy	247 596	550.21	565.29

Table 23 shows the energy used in the different equipment.

Table 23: Simulated Energy Use without Washing Machine but with Heat Recovery

	[MJ/year]	[kWh/year]
Shower	14742	4095
Dishwasher	3046	846
Total	17788	4941

By subtracting Table 23 from Table 21 the total recovered energy can be found to be 2 716 kWh/year. This result deviate a little from the result found chapter 6.3.4 for the solution district heating with pre heating of hot tap water and heating of building.

8 Economic Evaluation

To be able to calculate an estimate how much it is possible to save due to reduced usage of energy, it is crucial to have prices for the energy purchased.

Table 24 shows the prices for electricity including tax and other standard fees in øre/kWh (Statistics Norway, 2012):

Table 24: Electricity prizes in Norway [øre/kWh]

Year	2009	2010	2011
Energy prize excluding tax	35,2	46,8	44,6
Energy price including tax	42,9	57,1	54,3
Fixed net cost excl. Taxes	24,7	27,6	27,8
Fixed net cost including taxes	42,9	46,7	47,2
Total excluding Taxes	60,0	74,4	72,4
Total including taxes	85,9	103,8	101,5

If the main source for heating of hot tap water is electricity, then the prices from Table 24 has been used in the economic calculations. If on the other hand the main source is district heating, then the prices obtained from Hafslund Fjernvarme (Hafslund Fjernvarme, 2012), shown in Table 25, has been used.

Table 25: District Heating Prices from Hafslund Fjernvarme [øre/kWh]

Year	2009	2010	2011
Energy price excluding tax	53.20	70.78	62.17
Energy price including tax	66.50	88.47	77.71

For the economic evaluations an interest of 6.5 % has been found to be reasonable for such an investment. The yearly savings (B) can be found by multiplying the price for district heating in 2011 from Table 23 with the calculated energy savings from Table 7.

8.1 Shower Installations

For the shower installations it has been assumed an economic lifetime of 20 years.

8.1.1 Heat Exchanger with District Heating

The investment cost for the different units for heat recovery is found in Table 26 (Meander Heat Recovery, 2012)

Table 26: Investment Cost for Shower Heat Recovery Units

	For three units [NOK]	Installation Kit for three units [NOK]
VX-pipe	16 200	1 185
HX-drain	30 900	1 965
HeatSnagger	4 170	-

By using Equation 16 and Equation 17 from chapter 2.5 the present value and repayment time could be found. These results are based on the data from Attachment 1: Measured Data. The results mentioned in Table 27 could be very different with other measured data.

Table 27: Present Value and Repayment Method for Shower Installations with District Heating

	Present value [NOK]	Pay-back Time [years]
VX-pipe	3 233	14.7
HX-drain	-15 988	>20
HeatSnagger	3 339	8.1

From Table 27 the HeatSnagger installation has the shortest pay-back time and is the most beneficial installation over 20 years. The HX-drain is the worst with a pay-back time longer than the economic lifetime. Although the HeatSnagger comes out as the most beneficial one over 20 years, the VX-pipe would be a lot more beneficial after these 20 years. Unfortunately the VX-pipe requires some room for the installation (Meander Heat Recovery).

The HeatSnagger is best suited for cabinet showers and not for showers straight on the floor, but it is the cheapest installation and has the shortest pay-back time of 8.1 years. These pay-back periods could be severely reduced with other data for shower usage.

For showers straight on the floor and too little room for installation of a VX-pipe the HX-drain would be most logical installation. On the other hand it can be hard to defend an investment of nearly 11 000 NOK pr. unit with a pay-back time longer than the economic lifetime of 20 years.

8.1.2 Heat Exchanger with Electrical Heating

The Investment costs would be the same here as in Table 26

The yearly savings could then be found by multiplying the price for electricity in 2011 from Table 24 with the calculated energy savings from Table 7.

Table 28: Present Value and Repayment Method for Shower Installations with Electricity

	Present value [NOK]	Pay-back Time [years]
VX-pipe	9 546	9.9
HX-drain	-10 822	>20
HeatSnagger	5 638	5.8

The drastic change in present value and pay-back time reflects how sensitive the investments are to the energy price.

In this case it is the VX-pipe which would be the most beneficial installation when the lifetime of 20 years us taken into consideration.

8.2 Dishwasher Installation

The price for the recovery unit for the dishwasher was not found but it is here calculated a maximum cost for the installation by using Equation 16 and set the present value equal to zero.

In chapter 6.3.2 there were found two different amounts of recovered energy based on two different washing cycles for the dishwasher. This gave two different answers as shown in Table 29.

Table 29: Maximum Investment Cost for Dishwasher Heat Recovery System

	Recovered Energy per Unit [kWh/year]	Maximum Investment Cost [NOK]
Washing cycle from Figure 10	333	3 720
Estimated washing cycle from figure Figure 7	133	1 484

These results show that the investment cost can't be very high before the investment gives a negative outcome. In the case building the dishwasher are using a lot more energy than the energy assumed in the report made on this heat recovery unit (De Paepe, et al., 2002). The report has estimated an average use of 268 kWh/year for one dishwasher. The number used in this report is more than 2.5 times this value.

8.3 Centralized Grey-water Heat Recovery

Since it is not any Investment prices to obtain on these systems there are made economic evaluations based on the pay-back time.

8.3.1 Heat Exchanger with Washing Machine and District Heating

Figure 24 shows the maximum investment cost with the respective pay-back time for the investment without losing money. In this particular case it is the amount of district heating which is reduced.

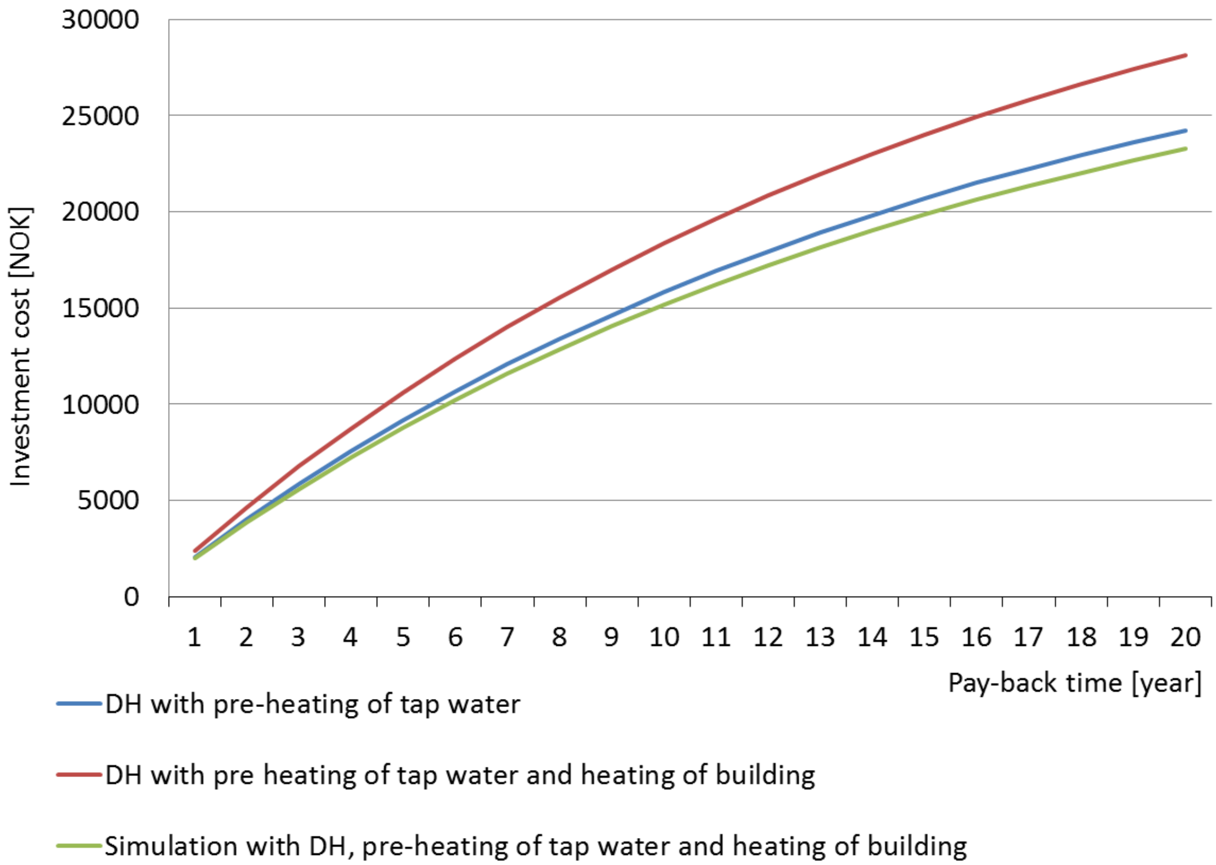


Figure 24: Maximum Investment Cost with District Heating

The scenarios with accumulation tank are not taken into consideration regarding the economic calculations because there would most likely not be any accumulation tanks installed when the building has district heating (see Attachment 3: Economic Evaluation for more detailed maximum investment costs).

Regarding the economic results in Figure 24, the simulation should have had the same outcome as the DH with pre-heating of tap water and heating of building. This is unfortunately not the case here. The reason for this deviation could be because it was implemented wrong in EnergyPlus or there are some heat losses which are taken into account in EnergyPlus which was disregarded in the hypothetical estimations.

The maximum investment cost for the installation for the present value to be equal to zero for the two different theoretical estimates are 24 240 NOK and 28 128 NOK. The simulation can be compared to the solution with pre-heating of tap water and heating of building and has a maximum investment cost of 23 256 NOK.

8.3.2 Heat Exchanger with Washing Machine and Electric Heating

With electrical heating the Investment cost can be a bit higher due to the electricity price is higher than the price for district heating as shown in Figure 25.

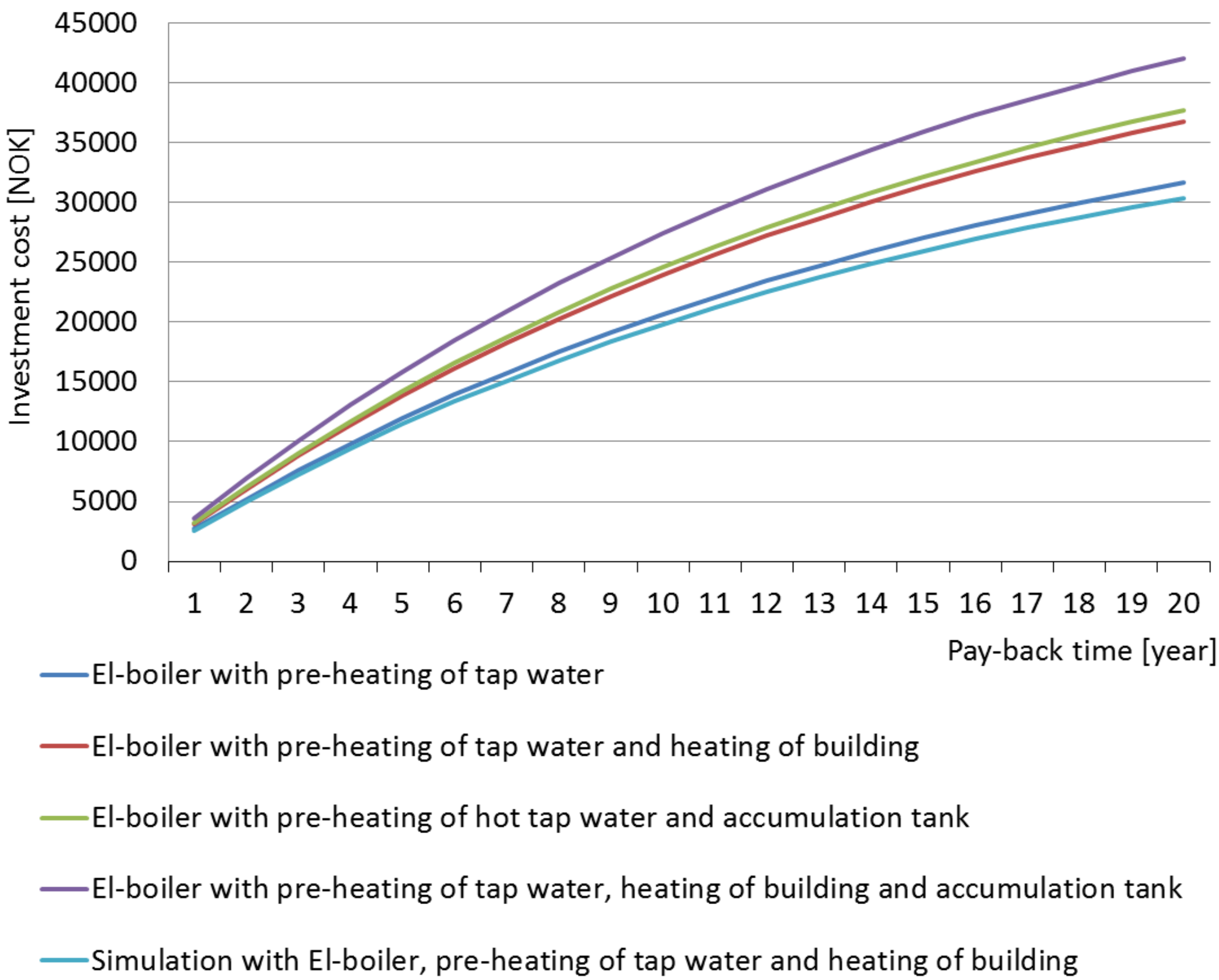


Figure 25: Maximum Investment Cost with Electrical Heating

As shown in Figure 25 the maximum investment cost for a system with present value equal to zero after 20 years can vary from 31 661 NOK to 42 040 NOK depending on which system is installed. This is not a very large amount of money for an installation which needs independent piping for the washing machine and shower. The Simulation has a maximum investment cost of 30 375 NOK which deviates from the hypothetical estimated solution for the same system which have a maximum investment cost of 36 739 NOK (see Attachment 3: Economic Evaluation for more detailed maximum investment costs).

It should be mentioned that the solutions with pre heating of tap water without an accumulation tank is not very realistic. Usually when there is an electrical boiler, then there is some sort of storage for the hot tap water. It is only presented in Figure 25 is to be able to compare it to the simulation. The systems correspond to Figure 16 and Figure 17 where the district heating feed line should be replaced with a line from the electrical boiler.

If there was a way of implementing the washing machine into the system without the negative effect the maximum investment cost for a system with preheating of tap water and heating of the building could be raised from 36 739 NOK to 41 771 NOK if the source of energy would be electricity.

9 Results

This chapter is just a summarization of the results in this report put together to give a better overview of the different solutions for heat recovery from grey-water.

9.1 Shower Installations

Table 30 and Table 31 give an overview of installation cost, recovered energy and economic evaluation.

Table 30: Overview of Results for Three Shower Installations using Electricity

	Investment Cost for Three Showers [NOK]	Percentage reduction in energy pr. shower [%]	Total energy recovered per year [kWh/year]	Present Value District Heating [NOK]	Pay-back Time District Heating [years]
HeatSnagger	4 170	15.6	877	9 546	8.1
HX-Drain	32 865	35.0	1 971	-15 988	>20
VX-Pipe	17 385	42.7	2 408	3 233	14.7

Table 31: Overview of Results for Three Shower Installations using District Heating

	Investment Cost for Three Showers [NOK]	Percentage reduction in energy pr. shower [%]	Total energy recovered per year [kWh/year]	Present Value Electric heating [NOK]	Pay-back Time Electric Heating [years]
HeatSnagger	4 170	15.6	877	5 638	5.8
HX-Drain	32 865	35.0	1 971	-10 822	>20
VX-Pipe	17 385	42.7	2 408	9 546	9.9

9.2 Centralized Grey-water Heat Recovery Unit for Case Building

Table 32 and Table 33 give an overview of the different installations illustrated in chapter 5.

Table 32: Overview of results for centralized heat recovery unit when energy source is electricity

	Maximum investment cost with present value equal zero after 20 years [NOK]	Efficiency	Recovered energy [kWh/year]
El-boiler with pre-heating of tap water and accumulation tank	37 678	78.7 %	3 369
El-boiler with pre-heating of tap water, heating of building and accumulation tank	42 039	87.8 %	3 759
Simulation with El-boiler, pre-heating of tap water and heating of building	30 375	63.4 %	2 716

Table 33: Overview of results for centralized heat recovery unit when energy source is district heating

	Maximum investment cost with present value equal zero after 20 years [NOK]	Efficiency	Recovered energy [kWh/year]
District heating with pre-heating of tap water	24 240	66.1 %	2 831
District heating with pre-heating of tap water and heating of building	28 128	76.7 %	3 285
Simulation with district heating, pre-heating of tap water and heating of building	23 256	63.4 %	2 716

9.3 Centralized Grey-water Heat Recovery Unit for Large Buildings

In this chapter of results it is looked into what would happen to the maximum investment cost if there should be installed a unit in a large building with 30 units with the same energy use as the measured data from Attachment 1: Measured Data.

It is here chosen to look at the district heating solutions since most large buildings is bound by law in Norway to connect to district heating if the buildings are built inside regulated area for district heating (Lovdata, 2012). The different municipal can also demand that new buildings shall be installed with a distribution system for water based heating even if they are not built inside a regulated area for district heating (Miljøverndepartementet, 2012).

Table 34 shows the maximum cost for a grey-water heat recovery system for a building with 30 apartments as well as the maximum cost if the pay-back time should not exceed 10 years.

Table 34: Maximum investment cost for a building with 30 apartments

	Maximum investment cost with present value equal zero after 20 years [NOK]	If pay-back time should be equal to 10 years [NOK]	Recovered energy [kWh/year]
District heating with pre-heating of tap water	242 404	158 152	28 310
District heating with pre-heating of tap water and heating of building	281 278	183 515	32 850

10 Discussion

Based on the results for a centralized grey-water heat recovery unit the maximum investment cost compared to all the work and equipment needed for such an installation is very small. It might therefore not be beneficial for small buildings to install such a system. But if one choose to look into building complexes with several apartments connected to such a system, the centralized heat recovery unit might become beneficial. There are also other large buildings with high consumption of hot tap water which could benefit from a grey-water heat recovery system. For example hotels would be ideal for such an installation. For a hotel to install single heat recovery units on each shower as well as on the dishwashers would be incredibly expensive and therefore a centralized system would maybe be more beneficial.

Regarding the shower systems compared with the data for hot tap water use from Attachment 1: Measured Data there are in particular one solution which stands out. The HX-drain would not be beneficial for this particular case building. The main reason for this would be the amount of energy used for hot tap water is lower than expected values compared to the Norwegian standard NS 3031. The amount of energy used for hot tap water in this case is a lot less than the estimated value in NS 3031 (Standard Norge, 2007). According to the standard the case building should have a total hot tap water consumption of 20 104 kWh which is a lot more than 13 407 kWh (Attachment 1: Measured Data. This would give very different results for the economic evaluation of the shower installations and the centralized heat recovery units.

For shower installations there is no way to make a common economic evaluation for all residential buildings. Each building has different use patterns and therefore has to be treated individually, but for a centralized grey-water heat recovery unit which could be connected to several hot tap water consumers, it should be possible to find an average consumption by gathering a lot of measured data from different buildings. It would then be possible to estimate an average hot tap water use for showers and dishwashers. This average could be used as an estimate for dimensioning and installation of a grey-water heat recovery unit for large buildings with several grey-water sources. The probability for the estimated average of being correct increases with the amount of hot tap water consumers connected to the grey-water heat recovery unit.

There are also some indirect benefits by installing a grey-water heat recovery system. For systems which would have an accumulation tank with a heating coil inside, the installed power could be reduced and still have an acceptable recharging time. This could give a reduced investment cost for the accumulation tank.

For a system connected to district heating, the total installed power in the heat exchanger for the district heating could be reduced since the temperature lift of the hot tap water has been lowered due to pre heating of water which enters the heat exchanger. Some district heating companies work with a fixed cost for installed power and this could be an indirect economic benefit from such a system. The only problem here is that the district heating companies could be negative to such a system due to reduced temperature difference over the heat exchanger. It is already a common problem in the district heat net that the temperature difference is reduced (Jæger, 2011). This lowers the efficiency of the district heat plant (Gurholt, 2011).

Regarding the economic evaluation done in this report the interest were set to 6.5 %. As mentioned before, this is a small interest for economic evaluations done by large companies to evaluate if an investment would give a positive result on the profit. If the calculations were done with an interest of 10.5 % which is a more realistic view, then the maximum investment cost for a grey-water heat recovery unit for a building with 30 apartments and district heating as the main source of energy would be 181 078 NOK for the solution with heating of the building and 210 116 NOK for the one with heating. So if this was compared to installing 30 single shower units instead the maximum investment cost would be 154 842 NOK and 202 245 NOK for the same conditions with the VX-pipe. The VX-pipe does require some room for installation (Meander Heat Recovery). The other to shower installations gives a lot smaller maximum investment costs. These are respectively 126 689 NOK for the HX-drain and 56 306 NOK for the HeatSnagger with district heating as the energy source. These numbers gives an indication that there is more to earn on installing a grey-water heat recovery unit if the investment cost is reasonable.

These maximum investment costs could be increased if an application for economic support for projects which reduces the total use of energy in a building would be sent to Enova (Enova, 2012).

11 Conclusion

It was looked into if a grey-water heat recovery unit is something which should be implemented in residential buildings. In this particular case it was for a building of 450 m^2 divided into three apartments on three different floors.

Regarding the grey-water heat recovery unit there were several different scenarios which was evaluated. The simplest system had only pre-heating of tap water and nothing else and the most advanced system had pre-heating of tap water, heating of building and an accumulation tank to store the recovered energy from the grey water heat recovery unit. There is no doubt lead to the most annual cost saving. Although this system shows the most potential it is also the most expensive system and is most likely not the best solution when the investment cost is taken into consideration. The simplest system would not be able to exploit as much of the grey-water which passes through the grey-water heat recovery as the more complicated systems. Most likely a grey water heat recovery unit in combination with an accumulation tank with a delayed filling system would prove itself to be the best system. This particular system would recover 3 379 kWh/year but could come in conflict with the district heating system if the building has district heating.

If district heating would be the source of energy for tap water, then the solution with heating of building should be evaluated. This system would recover 3 285 kWh/year according to the theoretical calculations. That is almost the same as the system with an accumulation tank but it might have a higher investment cost and could be the best solution for this scenario.

For a system having both an accumulation tank and heating of the building could be able to recover 3 759 kWh/year and the increase in recovered energy would most likely not justify the increase in the investment cost for such a system.

Regarding the results obtained from simulations done SIMIEN show that the total energy used in this building for hot water would be as much as 17.1 % of the total energy consumed in the building. This could be reduced to 10.9 % by installing a grey-water heat recovery unit. These numbers are based on an ideal case where almost all the grey-water passing through the grey-water heat recovery unit has some grade of heat exchange.

The results obtained from EnergyPlus for the system with pre-heating of tap water as well as heating of building show a little bit lower results than the calculated values done in chapter 6, but it still shows an energy savings potential of 2 716 kWh/year.

For small buildings there is a large possibility that small installations on single equipment could be more economic beneficial than a grey-water heat recovery unit, but this depends on the investment cost for the grey-water heat recovery unit.

For large buildings there is a large potential for heat recovery. In this report the maximum investment cost for a building with only three apartments could be too low for the investment to be beneficial.

For larger buildings the probability for a grey-water heat recovery unit to be profitable is a lot higher and it also reduces the supplied energy to the building more than the single equipment installations such as shower and dishwasher heat recovery units.

The fact that there are no benefits regarding the energy certification of a building regarding a grey-water heat recovery system could prevent developers from choosing to install such a system if there is no remarkable profit to make from such an installation. This put a lot of pressure on the economic benefit side of such a system and this might harm the progress for reducing energy use in buildings.

12 Further Work

Since there is not done so much research on this area there is a lot of further work which could contribute to developing a proper centralized grey-water heat recovery system. First of all more detailed measurements for grey-water needs to be obtained. This report was based electrical measurements over a short time period and it would be a lot better if there had been measured temperature and volume of the grey-water from showers and dishwashers over a longer time period.

The next step could be to look more detailed into the technical aspects of such an installation and build up a model and run some tests in a laboratory.

Before a pilot project would be installed, then there should be a rough estimate on how much it would cost to produce these centralized grey-water heat recovery unit to see if there are any profit to be made by producing these units.

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Attachment 1: Measured Data

The data in the attachment has been treated and severely reduced. The original data file had 30 384 rows and 10 columns.

	A	B	C		A	B	C
1	kWh varmtvannsbereder	kWh Vaskemaskin	kWh Oppvaskmaskin	41	1.3031		
2	11.004505	3.00472	2.075068333	42	1.29167		
3	8.393583333	1.981916667	2.06826	43	1.276438333		
4	7.80352	1.79014	2.032221667	44	1.268375		
5	7.000991667	1.467681667	2.010628333	45	1.25696		
6	6.934723333	1.282173333	1.980343333	46	1.230203333		
7	6.824396667	1.282065	1.97656	47	1.2063		
8	4.971905	1.112805	1.962453333	48	1.181028333		
9	4.371546667	0.797668333	1.943508333	49	1.171473333		
10	3.854848333	0.742181667	1.884885	50	1.1583		
11	2.958016667	0.507926667	1.873945	51	1.151826667		
12	2.659976667	0.443288333	1.832006667	52	1.125045		
13	2.330295	0.40775	1.828896667	53	1.115966667		
14	2.321133333	0.4065	1.819615	54	1.111996667		
15	2.188903333	0.36614	1.799925	55	1.107903333		
16	2.179563333	0.363818333	1.77406	56	1.106053333		
17	2.033486667		1.734173333	57	1.104016667		
18	2.027478333		1.709806667	58	1.087901667		
19	1.920308333		1.63959	59	1.068415		
20	1.906245		1.63492	60	1.033553333		
21	1.751328333		1.226741667	61	1.02357		
22	1.743501667		0.627753333	62	0.994793333		
23	1.710915			63	0.988991667		
24	1.641485			64	0.986671667		
25	1.581101667			65	0.964765		
26	1.558933333			66	0.958413333		
27	1.53445			67	0.951608333		
28	1.512175			68	0.941353333		
29	1.49809			69	0.932526667		
30	1.475768333			70	0.928608333		
31	1.474253333			71	0.91324		
32	1.47274			72	0.901465		
33	1.443563333			73	0.899615		
34	1.441425			74	0.895766667		
35	1.43236			75	0.879661667		
36	1.387345			76	0.869283333		
37	1.37535			77	0.867011667		
38	1.371045			78	0.865341667		
39	1.352095			79	0.863315		
40	1.325468333			80	0.86165		
41	1.3031			81	0.855975		

	A	B	C
82	0.85457		
83	0.849433333		
84	0.84383		
85	0.839391667		
86	0.824686667		
87	0.818956667		
88	0.803725		
89	0.800308333		
90	0.795425		
91	0.789901667		
92	0.785		
93	0.781355		
94	0.779851667		
95	0.779358333		
96	0.77604		
97	0.775718333		
98	0.773621667		
99	0.773463333		
100	0.771406667		
101	0.76741		
102	0.765548333		
103	0.76353		
104	0.761576667		

	A	B	C
105	0.760745		
106	0.75832		
107	0.752163333		
108	0.750833333		
109	0.750208333		
110	0.750061667		
111	0.7455		
112	0.741938333		
113	0.738031667		
114	0.735428333		
115	0.733265		
116	0.729548333		
117	0.727915		
118	0.72777		
119	0.72728		
120	0.726498333		
121	0.71903		
122	0.715766667		
123	0.702778333		
124	0.701966667		
125	0.698596667		
126	0.679536667		
127	0.67492		

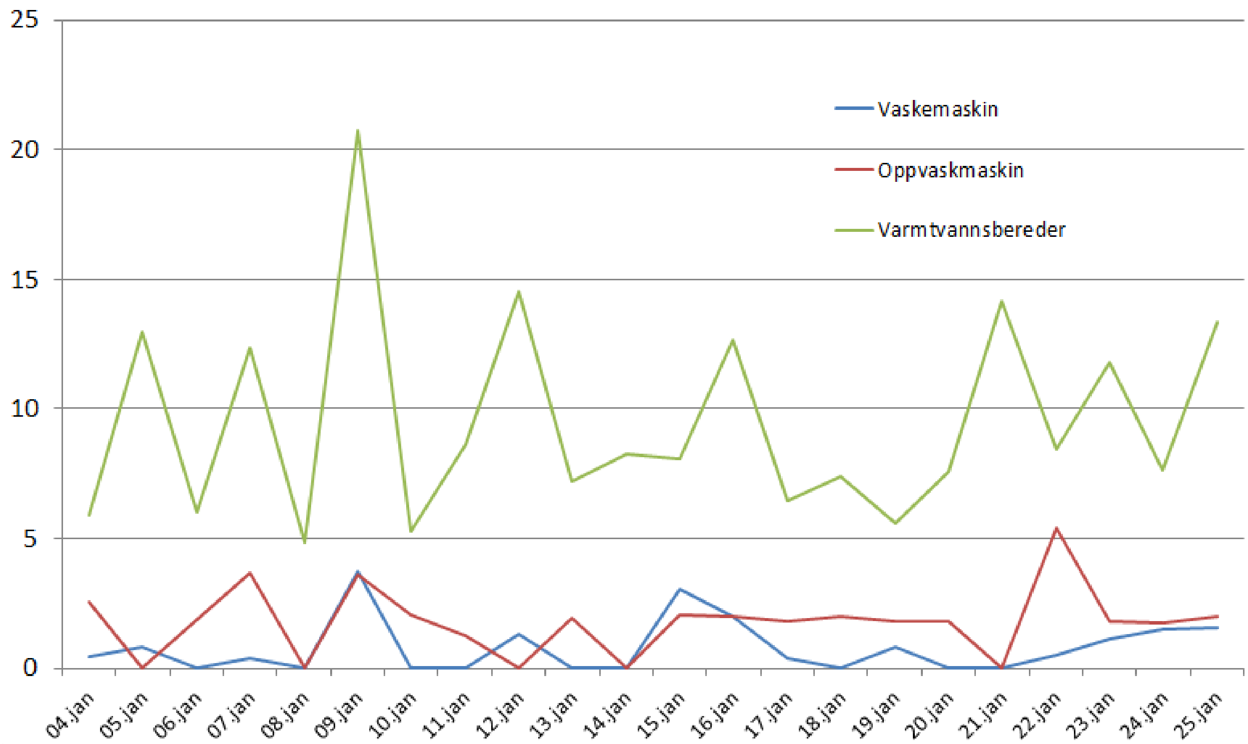
	Estimated pr.day	20 days	Estimated 1 year	Average kWh when on	Estimate for case building
Hot water boiler	9.57	191.49	3494.71	1.52	10484.14
Washing machine	0.80	15.96	291.21	1.06	873.63
Dish washer	1.87	37.44	683.20	1.78	2049.59
Total	**12.24**	**244.88**	**4469.12**	**4.37**	**13407.36**

VARMTVANNSBEREDER:
Antar at 60 % av varmt tappevann blir brukt på badet og at 90 % av varmt tappevann på badet er til

Total usage	Estimated pr.day	20 days	Estimert 1 year	For 3 units
Shower	5.17	103.41	1887.15	5661.44
Sink in bathroom	3.45	68.94	1258.10	3774.29
Sink in kitchen	0.96	19.15	349.47	1048.41

Antar tre dusjinger pr. dag er satt til:
3 * 4min
10,5 L/min (0,000175 m3/s pr dusj)
31,5 L/min (0,000525 m3/s totalt for de tre)
1,708 kWh pr. dusj
5,124 kWh for alle tre totalt

	Vaskemaskin	Oppvaskmaskin	varmtvannsbereder	Samlet	
04.jan	0.44278833	2.521356667	5.898146667	8.86229166	Tirsdag
05.jan	0.79816833	0.00028167	13.0000583	13.7985083	Onsdag
06.jan	0	1.873945	6.0185615	7.8925065	Torsdag
07.jan	0.36381833	3.67226	12.3555317	16.39161	Fredag
08.jan	0	0	4.84128833	4.84128833	Lørdag
09.jan	3.74690167	3.61526333	20.7048433	28.0670083	Søndag
10.jan	0	2.072595	5.2907	7.363295	Mandag
11.jan	0	1.24183667	8.644125	9.88596167	Tirsdag
12.jan	1.28217333	0	14.5253267	15.8075	Onsdag
13.jan	0	1.94353333	7.22748667	9.17102	Torsdag
14.jan	0	0	8.26244333	8.26244333	Fredag
15.jan	3.072205	2.06902667	8.075655	13.2168867	Lørdag
16.jan	1.9819667	2.01279333	12.6797667	16.6745267	Søndag
17.jan	0.36614	1.835805	6.48521167	8.68715667	Mandag
18.jan	0	1.971995	7.39037	9.362365	Tirsdag
19.jan	0.81426667	1.83699	5.606945	8.25820167	Onsdag
20.jan	0	1.81975833	7.59290667	9.412665	Torsdag
21.jan	0	0	14.1863067	14.1863067	Fredag
22.jan	0.50792667	5.40610333	8.42418	14.33821	Lørdag
23.jan	1.112805	1.799925	11.8232783	14.7360083	Søndag
24.jan	1.47488333	1.77406	7.666795	10.9157383	Mandag
25.jan	1.54637833	1.9852535	13.3488783	16.8805101	Tirsdag
	17.51042169	39.45278183	210.0488048	267.012008	
	290.5138144	654.5575167	3484.900626	4429.97196	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Oppvaskmaskin
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Attachment 2: Heat Exchanger Calculations

	mh [l/s]=[kg/s]	mgw [l/s]=[kg/s]	Ch [kW/K]	Cc [kW/K]	C [1]	Qmax [kW]	*Qmax/dT [W/K]*
Shower	0.127604167	0.175	0.5359375	0.735	0.729166667	15.542188	*0.4440625*
WM	0.048125	0.066	0.202125	0.2772	0.729166667	7.074375	*0.202125*
DW	0.08	0.08	0.336	0.336	1	16.128	*0.336*

HEX	GreyWaterTank	
AreaSurTank	0.835125619	m2
AreaColdPipes	0.010103175	m2
U value	938	W/m2K
Volume	0.05	m3
Diameter	0.281394792	m
Height	0.803985121	m
H/D ratio	2.857142857	(0.8<H/D<2.5)

Constant	
Cp,water	4.2
π	3.141592654

Total amount of water used pr. year		
Shower	100.603125	m3
Washing Machine	15.76575	m3
Dish Washer	36.792	m3
Total	153.160875	m3

Centralised heat recovery

	Heat transfer	Energy transfered
Recovery from Shower	12.8625	2816.8875

HEX		
V SmallPipe	6.36	L
D SmallPipe	0.020	m
AreaSurTank	0.994	m2
AreaColdPipes	1.571	m2
U value	925	W/m2K
Volume	0.05	m3
Width and length	0.224	m
Height	1.000	m
H/D ratio	4.47215	
Amount of GW	42.15	L
Epselon SH	0.8	
NTU SH	2.710040031	
Epselon DW	0.8121	
NTU DW	4.3227	
Epselon WM	0.956821248	
NTU WM	7.185712204	
Qmax shower	16.078125	kW
Q shower	12.8625	kW
Qmax dishwasher	14.112	kW
Q dishwasher	11.46069158	kW
Qmax WashMach	5.457375	kW
Q WashMach	5.221732357	kW
E saved SH	2816.8875	kWh
E saved DW	1464.10335	kWh
E saved WM	475.1776445	kWh

Temperature		
Th,in shower	37	C
Th,in DishWash	49	C
Th,in WashMach	34	C
Tc,in	7	C
Delta T hot side	6	C

For mc mh and C	Temperature		flow	
Shower	42	C	0.175	l/s
WashMach	42	C	0.0835	l/s
DishWash	55	C	0.0835	l/s
HotWater	55	C		
ColdWaterIn	7	C		

Total usage	Estimated pr.day	20 days	Estimated 1 year	Average kWh when on	For 3 units
Hot water boiler	9.574559167	191.49118	3494.714096	1.519771296	10484.14229
Washing machine	0.79783875	15.956775	291.2111438	1.063785	873.6334312
Dish washer	1.871768083	37.435362	683.1953504	1.78263627	2049.586051
Total	**12.244166**	**244.88332**	**4469.12059**	**4.366192566**	**13407.36177**

VARMTVANNSBEREDER:
Antar at 60 % av varmt tappevann blir brukt på badet og at 90 % av varmt tappevann på badet er til dusjen.

Total usage	Estimated pr.day	20 days	Estimated 1 year	For 3 units
Shower	5.17026195	103.40524	1887.145612	5661.436835
Sink in bathroom	3.4468413	68.936826	1258.097075	3774.291224
Sink in kitchen	0.957455917	19.149118	349.4714096	1048.414229

This is based on ideal floe. No heat loss from shower head or dish washer or washing machine before it reaches the tank

Flow through tank	Energy pr. day	20 days	Estimated 1 year	For 3 units
With WashMach	7.839868783	156.79738	2861.552106	8584.656318
Without WasMach	7.042030033	140.8406	2570.340962	7711.022887

	Power HEX	T before HEX	T after HEX	Tp - Tcold	E saved	kr Saved
HeatSnagger	4 kW	7 C	12.44 C	5.4422 dT	880.30	893.51
HXDrain	9 kW	7 C	19.24 C	12.2449 dT	1980.68	2010.39
VXPipe	11 kW	7 C	21.97 C	14.9660 dT	2420.83	2457.14

Year	2009	2010	2011
Energy price excluding tax	35.2	46.8	44.6
Energy price including tax	42.9	57.1	54.3
Fixed net cost excl. Taxes	24.7	27.6	27.8
Fixed net cost including taxes	42.9	46.7	47.2
Total excluding Taxes	60	74.4	72.4
Total including taxes	85.9	103.8	101.5

486.87	1460.62
-6732.04	-20196.11
-633.60	-1900.80

	PV DH	PV EL	
HS	1876.87	2451.45	NOK
HX	4222.96	5515.77	NOK
VX	5161.40	6741.50	NOK

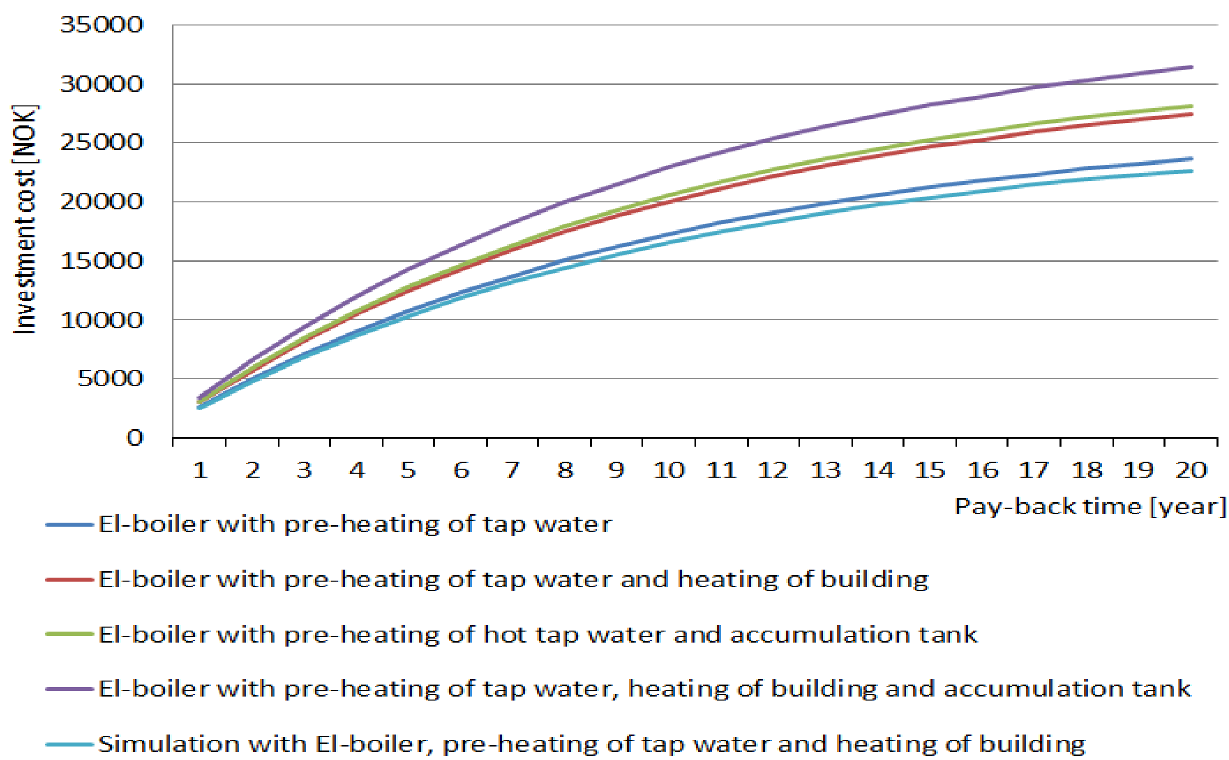
Year	2009	2010	2011
Energy price excluding tax	53.20	70.78	62.17
Energy price including tax	66.50	88.47	77.71

	x30 PV DH	x30 PV EL	
HS	56306.17	73543.64	NOK
HX	126688.88	165473.19	NOK
VX	154841.96	202245.01	NOK

Attachment 3: Economic Evaluation

Icost with el

Pay-back time	pre He	Pre-H and Build.	w/Boil & PreH	w/boil PH &Bui	Simulation
1	2600.420814	3017.443439	3094.60181	3452.837104	2494.78733
2	4953.742819	5748.161483	5895.146434	6577.576565	4752.513421
3	7083.44599	8219.399532	8429.575959	9405.395081	6795.704453
4	9010.779176	10455.81406	10723.17734	11964.50686	8644.746112
5	10754.97211	12479.7186	12798.8347	14280.44512	10318.08698
6	12333.42724	14311.30643	14677.25764	16376.31685	11832.42261
7	13761.89343	15968.85197	16377.18791	18273.03335	13202.86209
8	15054.62302	17468.89319	17915.58635	19989.51887	14443.07881
9	16224.51404	18826.39655	19307.80212	21542.89943	15565.44689
10	17283.23895	20054.90638	20567.7259	22948.67369	16581.1646
11	18241.36104	21166.67998	21707.92842	24220.86759	17500.36616
12	19108.43986	22172.80994	22739.7859	25372.17429	18332.22277
13	19893.12657	23083.33479	23673.59357	26414.08081	19085.03418
14	20603.25029	23907.33917	24518.66839	27356.98263	19766.31147
15	21245.89619	24653.0445	25283.44198	28210.28745	20382.85201
16	21827.47619	25327.89095	25975.54478	28982.509	20940.80725
17	22353.79293	25938.61172	26601.88216	29681.35204	21445.74412
18	22830.09767	26491.3002	27168.70331	30313.78918	21902.70056
19	23261.14269	26991.47077	27681.66363	30886.13048	22316.2358
20	23651.22868	27444.11382	28145.88111	31404.0864	22690.47584



Icost with dh	pre He	Pre-H and Build.	w/Boil & PreH
1	1990.923167	2310.202262	1910.048507
2	3792.66359	4400.883043	3638.599192
3	5423.19791	6292.901849	5202.898454
4	6898.794579	8005.136062	6618.553895
5	8234.17618	9554.669287	7899.690041
6	9442.666317	10956.9618	9059.089268
7	10536.32255	12226.00479	10108.31934
8	11526.0567	13374.46	11057.84881
9	12421.74371	14413.78597	11917.1515
10	13232.32019	15354.35246	12694.801
11	13965.87356	16205.54386	13398.5562
12	14629.72277	16975.85281	14035.43873
13	15230.49129	17672.96499	14611.80301
14	15774.1732	18303.83573	15133.39965
15	16266.19303	18874.75949	15605.43281
16	16711.45985	19391.43257	16032.61213
17	17114.41624	19859.01002	16419.19976
18	17479.08266	20282.15703	16769.05281
19	17809.09752	20665.0955	17085.66191
20	18107.75351	21011.64615	17372.18598