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Analysis of change in design procedures for heat pump systems in nZEB

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Master's Thesis

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MASTER THESIS

for

Student Thomas Murer

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Analysis of change in design procedures for heat pump systems in nZEB*Analysen av endringer i designprosedyrer for varmepumpesystemer i nZEB***Background**

The goal for the project work is to analyse the change in design procedures of heat pump systems when the building energy performance is progressively improved, i.e. starting from the standard performance of today, to the passive house standard and, finally, to the nZEB level. This is done using simple modelling approaches implemented in Matlab combined with Modelica, or alternatively, Matlab combined with TRNSYS. This proposal is the continuation of a Master student work of the academic year 2012-2013. The present contribution will further improve the system modelling and the analysis of results. In parallel, other techniques will also be investigated in detail, such as the impact of energy storage (e.g. storage tank, or storage in the ground when using ground-source heat pump). The project work is connected to the NTNU-SINTEF Zero Emission Building (ZEB) activity on development of an early-stage design tool for the selection of renewable thermal energy supply systems for nZEB (near Zero Emission Buildings) as well as the IEA HPP Annex 40 on heat pumps for nZEB. Developments should be done in collaboration with another student project (Mikkel Ytterhus) working on the same tool but with non-overlapping objectives.

Objectives:

- **Improvement** of the modelling procedure and of its implementation:
 1. Better models: Implement, in Modelica or TRNSYS, the methodology of cost-optimal nZEB using heat pump technology currently developed in Matlab.
 2. Add new components: stratified thermal energy storage tank, solar thermal panels, piping, heating and cooling batteries, overall system control and ground storage (depending on the component model available).
- **Sensitivity analysis** on the influence of the load profile on the heat pump performance (space-heating, space-cooling and domestic hot water).

The following tasks are to be considered:

1. Literature review of related topics
2. Critical analysis of the previous Master thesis and the related first-generation Matlab tool.
3. Motivate the choice of another simulation platform (Matlab-Modelica or Matlab-TRNSYS).
4. Implement the cost-optimality methodology in the selected platform.
5. Sensitivity analysis on the influence of the load profile on the heat pump performance.
6. Discussion of results and comparison with previous results
7. Make a scientific paper of the main results for the work
8. Make proposal for further work

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.

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- Work to be done in lab (Water power lab, Fluids engineering lab, Thermal engineering lab)
 Field work

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Preamble

This thesis is the written final work of my Master's degree in the "MRU Environmental Engineering" at the "University of Applied Science Rapperswil" (HSR). I wrote this thesis during an Erasmus exchange at the department of "Energy and Process Engineering" at the "Norwegian University of Science and Technology" (NTNU). The work is the continuation of a previous Master's thesis, which was carried out in the 2014 fall semester.

This thesis describes the simulation tool for "Zero Emission Building" (ZEB) and the main results are listed and discussed. This simulation tool provides the possibility to investigate different energy supply strategies for office buildings and to compare them on the level of costs, CO₂ emission and performance.

The simulation tool (SimTool) is based on Matlab and Matlab/Simulink which allowed me to bring in my previous experiences with these tools. Nevertheless I have learned a lot of additional skills using and coupling the two tools.

A team of supervisors always supported the work for my project. My main supervisor was Associate Professor Laurent Georges with whom I discussed all the details about the modelling of the SimTool. I benefitted immensely from his experience in building heating system. The two co-supervisors, Maria Justo Alonso a research assistant at NTNU and research scientist at SINTEF and Professor Trygve Magne Eikevik were a great support when it came to discussions about the heat pump and the integration of the heat pump in the building system. At the same time as I was working on the thesis my colleague Mikkel Ytterhus was working on the tool as well. His task was to analyse the ground source model.

Writing my thesis abroad was a great experience; I got exposed to new surroundings and new technical standards. All the new knowledge I have learned and gathered here will help me on my further path as an engineer.

Trondheim January 2015



Thomas Murer

Summary

The work done in this master's thesis is a continuation of a previous thesis on an early decision tool on the heat pump (HP) integration in office buildings. The simulation tool (SimTool) proposed in this thesis enables the user to take decisions about the best energy supply system for an office building based on costs, energy performance and CO₂ emissions.

The original simulation tool was critically reviewed to formulate the improvements that should be implemented in the new tool. According to this review the main fields of improvement were found to be the modelling of the hydraulic system including the HP, the buffer tanks (BT) and the ground source model (GSM). Those requirements motivated the choice of Matlab/Simulink for the hydraulic system and Matlab as the executing program. To build up the different hydraulic systems in Matlab/Simulink the Carnot toolbox is used. The algorithm which allows the connection between those two tools as well as physical model behind the blocks used in Matlab/Simulink are shown in this report.

The definition of the different building heating system (BHS) combinations was done based on the state of art for the HP integration in office buildings, since the final version of this SimTool should be able to design the best building heating system with the components available on the market. The implementation of the costs and the CO₂ emissions is carried out in the same way as in the previous simulation tool.

The SimTool was first proven by analysing the performance of the different components like BT, HP and GSM and comparing it with the results of the previous thesis. Afterwards the simulation tool was used to investigate the influence of different parameters on the system performance. The results of this analysis are shown in the report, and the main results are summarized below.

- When deciding on which HP system to use in a certain office building it is very important to have accurate values for the cost parameters, since they have a big influence on the optimal coverage factor (OCF) of the HP.
- The size as well as the layout of the BT has a strong impact on the HP-performance and the OCF.

Summary (Norwegian)

Denne masteroppgaven omhandler utviklingen av et tidligfase beslutningsverktøy for energisystemer i kontorbygg tilknyttet varmepumpeløsninger og er en videreføring av en tidligere master med samme tema. Hensikten med beslutningsverktøyet er å hjelpe brukeren til å finne optimal beslutningsløsninger for bygget basert på kostnader, energibruk og CO₂-utslipp.

Som en start ble beslutningsverktøyet utviklet av Småland grundig analysert for å kartlegge hvilke områder som trengte forbedringer. Det ble funnet at de viktigste områdene for forbedring var det vannbårne systemet inkludert varmepumpen, buffertankene og modelleringen av grunnvarmesystemet. Det ble videre funnet hensiktsmessig å bruk Matlab/Simulink til å utføre simuleringer av systemet og styre simuleringen fra Matlab programmet. Det hydrauliske systemet ble satt opp ved hjelp av Carnot biblioteket tilknyttet Matlab/ Simulink. Algoritmen brukt til å knytte sammen Matlab og Simulink i tillegg til den fysiske modellen bak blokkene i Matlab/ Simulink er vist i rapporten.

De forskjellige oppvarmingsløsningene inkludert er basert på det nyeste innen varmepumpedesign for kontorbygg. Det endelige beslutningsverktøyet skal være i stand til å simulere optimale systemløsninger med de komponentene som er tilgjengelig på markedet. Kostnader og CO₂-utslipp er utregnet på samme måte som i den tidligere masteroppgaven.

Beslutningsverktøyet ble først testet ved å sammenligne resultater med den tidligere oppgaven. Deretter ble forskjellige parametere endre for å se hvordan dette endre resultatene fra simuleringer. Disse resultatene er beskrevet i rapporten og de viktigste funnene beskrevet under:

- For kunne finne den optimale varmepumpeløsningen for et kontorbygg er det avgjørende å bruke riktige kostnader ettersom dette har en avgjørende betydning for den optimale effektdekningsgraden til varmepumpen.
- Både størrelsen og designe av buffertankene har en sterk innvirkning på varmepumpens ytelse og optimal effektdekningsgrad.

Summary (German)

Diese Masterthesis ist die Anschlussarbeit an eine vorhergegangene Masterthesis, welche sich mit der Entwicklung eines Entscheidungstool für die Wärmepumpenintegration in Bürogebäuden beschäftigt. Das während der Thesis erarbeitete Simulationstool erlaubt es dem Benutzer das beste Heizungssystem in Hinblick auf Kosten, CO₂ Emissionen und Energieperformance auszuwählen.

Zuerst wurde das ursprüngliche Simulationstool kritisch geprüft um daraus Schlüsse für das weitere Vorgehen ziehen zu können. Dabei wurde Verbesserungspotential im Bereich der Modellierung des hydraulischen Systems, welches die Wärmepumpe, den Puffertank und das Bohrloch umfasst, erkannt. Um diese Anforderungen abzudecken wurde die Software Matlab/Simulink für den Aufbau des hydraulische Systems und Matlab für das Ausführen der Simulation ausgewählt. In Matlab/Simulink wurde hierzu die Carnot Toolbox verwendet. Neben den Simulationsmodellen ist auch der für die Kopplung dieser beiden Programme verwendete Algorithmus in diesem Bericht beschrieben.

Um sicher zu gehen, dass die verwendeten Komponenten auf dem Markt erhältlich sind, wurde das Heizungssystem anhand des aktuellen Stands der Technik ausgelegt. Zur Berechnung der Kosten sowie der CO₂ Emissionen wurde das gleiche Verfahren wie in der vorhergegangenen Masterarbeit verwendet.

Die Simulationsresultate sind zuerst validiert worden und mit den Ergebnissen aus der vorhergegangenen Arbeit verglichen worden. Zusätzlich ist noch der Einfluss unterschiedlicher Parameter oder Komponenten auf das Gesamtsystem untersucht worden. Die Ergebnisse dieser Untersuchungen sind im Bericht aufgeführt, untenstehend sind die Hauptideen zusammengefasst.

- Der Entscheid welches Wärmepumpensystem für ein Gebäude verwendet wird hängt sehr stark von den verwendete Kostenparametern ab. Deshalb ist es wichtig die verwendeten Parameter genau zu prüfen.
- Der Tank mit seiner Grösse und auch seiner Bauweise hat einen sehr grossen Einfluss auf die Kosten sowie auch den optimalen Deckungsgrad der Wärmepumpe.

Nomenclature

List of abbreviations

Abbreviation	Meaning
HP	Heat pump
ASHP	Air source heat pump
GSHP	Ground source heat pump
BH	Borehole
BUH	Backup heater
COP	Coefficient of performance
SPF	Seasonal performance factor
OCF	Optimal coverage factor
CO ₂	Carbon Dioxide
ZEB	Zero emission building
BT	Buffer tank
PV	Photovoltaic
HE	Heat exchanger
DHW	Domestic hot water
LMTD	Logarithmic mean temperature difference
NTU	Number of transfer units
DOT	Design outdoor temperature
THB	Thermo-hydraulic bus
FMI	Functional mock-up interface
FMU	Functional mock-up unit
EN	European norm
DIN	Deutsches Institut für Normung e.V.

Table 1: List of abbreviations

List of Symbols

Symbol	Unit	Description
A	[m ²]	Area emission system
a_{comp}	[-]	Annuity factor for a certain component
$C_{ann.inv}$	[NOK]	Annual investment cost
$C_{main.BUH}$	[NOK]	Maintenance cost BUH
$C_{main.HP}$	[NOK]	Maintenance cost HP
$C_{main.BUH}$	[NOK]	Maintenance cost BUH
$C_{op.HP}$	[NOK]	Operational cost HP
$C_{op.Pump}$	[NOK]	Operational cost pump
$C_{op.BUH}$	[NOK]	Operational cost BUH
c_{el}	[NOK/kWh]	Cost electrical energy per kWh
cp_{in}	[J/kg*K]	Specific heat capacity of the fluid at the inlet
cp_{heat}	[J/kg*K]	Specific heat of the heating water
$ctrl_{Pump}$	[-]	Control signal for the pump
I_{comp}	[NOK]	Investment cost for a certain component
ir	[-]	Interest rate
\dot{m}_{in}	[kg/s]	Mass flow of the inlet
\dot{m}_{DHW}	[kg/s]	Mass flow of the DHW
$\dot{m}_{max.heat}$	[kg/s]	Maximal mass flow of the heating system
n_{comp}	[-]	Lifetime for a certain component
$P_{el.in}$	[W]	Electrical power input
$Q(t)$	[W]	Time dependant heating power
Q_{nom}	[W]	Heating power at nominal conditions
Q_{DHW}	[W]	Heating power requirement of the DHW system
Q_{Heat}	[W]	Heating power requirement of the heating system
r	[-]	Radiator exponent
T_{in}	[°C]	Inlet temperature
$T_{in}(t)$	[°C]	Time dependant inlet temperature

T_{out}	[°C]	Outlet temperature
$T_{out}(t)$	[°C]	Time dependant inlet temperature
$T_{s.nom}$	[°C]	System temperature at nominal conditions
$T_s(t)$	[°C]	Time dependant system temperature
$T_{room.nom}$	[°C]	Room temperature at nominal conditions
$T_{room}(t)$	[°C]	Time dependant room temperature
dT_{heat}	[°C]	Temperature difference over the emission system
U	[W/m ² *K]	Heat transfer coefficient at emission system
ρ	[kg/m ³]	Density

Table 2: List of symbols

Contents

Preamble	3
Summary	4
Summary (Norwegian)	5
Summary (German)	6
Nomenclature	7
Contents	10
Table of Figures	13
Table of Tables	16
Table of Equations	17
1 Introduction	18
1.1 Method	19
1.1.1 Main goal	19
1.1.2 Sub-goals	19
1.2 Thesis structure	20
2 Simulation tool	21
2.1 Review previous tool	21
2.2 Software	23
2.2.1 Selection	23
2.2.2 Carnot toolbox	25
2.2.3 Functional Mockup Interface	26
2.3 Algorithm	27
2.4 Cost implementation	28
2.4.1 Operational costs	28

2.4.2	Annual investment cost.....	29
2.5	Emission implementation.....	29
3	System.....	30
3.1	System combinations.....	30
3.2	Components.....	32
3.2.1	Heat pump.....	33
3.2.2	Tank	38
3.2.3	Electric heater	42
3.2.4	Bio boiler	42
3.2.5	Gas boiler.....	42
3.2.6	Ground source	42
3.2.7	Heat exchanger.....	43
3.2.8	DHW mixer.....	43
3.2.9	Emission system	44
3.3	Loads.....	49
3.3.1	Heating/cooling loads.....	50
3.3.2	DHW loads.....	51
4	Results.....	53
4.1	Proof of Concept.....	54
4.1.1	Supply temperatures.....	54
4.1.2	Delivered power	55
4.1.3	Tank performance.....	56
4.1.4	Heat pump performance.....	59
4.1.5	Delivered energy	62
4.2	Comparison previous thesis	64
4.3	Impact parameters.....	67

4.3.1	Impact building	67
4.3.2	Impact BUH.....	69
4.3.3	Impact tank layout.....	71
4.3.4	Impact Tank Size	74
4.3.5	Impact tank control system.....	77
4.3.6	Impact emission system	79
4.3.7	Impact ground temperatures	81
4.3.8	Impact DHW-Profile	84
4.3.9	Impact Cost Parameters.....	85
4.4	Air source heat pump.....	87
5	Conclusion.....	89
6	Further work.....	91
7	Reflexion.....	93
7.1	Expenditure of time	93
7.2	Expression of thanks.....	94
8	Source	95
	Appendix	96

Table of Figures

Figure 1: Simulation algorithm	27
Figure 2: System boundaries.....	30
Figure 3: Parameters THB vector	32
Figure 4: Characteristic curve 11kW GSHP	33
Figure 5: Layout heating mode GSHP	35
Figure 6: Layout free cooling mode GSHP.....	36
Figure 7: Layout forced cooling mode GSHP.....	36
Figure 8: Layout heating mode ASHP	37
Figure 9: Layout cooling mode ASHP	38
Figure 10: Sketch buffer tank 1	39
Figure 11: Sketch buffer tank 2.....	40
Figure 12: Repeating sequence set temperature.....	41
Figure 13: Layout DHW mixer	44
Figure 14: Layout emission system	45
Figure 15: Control-block heating.....	46
Figure 16: Signature curve floor heating	47
Figure 17: Design office building.....	49
Figure 18: Power requirement passive house.....	51
Figure 19: DHW load curve for one week	52
Figure 20: Naming results.....	53
Figure 21: Supply temperatures (P_GS_EH_F_BT1 / 40 kW)	54
Figure 22: Delivered power (P_GS_EH_F_BT1 / 40 kW)	55
Figure 23: Temperatures DHW-tank on different heights (P_GS_EH_F_BT1 / 40 kW)..	56
Figure 24: Temperatures heating-tank on different heights (P_GS_EH_F_BT1 / 40 kW)	56

Figure 25: Temperatures DHW-tank on different heights two weeks (P_GS_EH_F_BT1 / 40 kW)	57
Figure 26: Thermal energy loses at DHW-tank (P_GS_EH_F_BT1)	58
Figure 27: Thermal energy loses at heating-tank (P_GS_EH_BT1)	58
Figure 28: HP temperatures (P_GS_EH_F_BT1 / 6 kW)	59
Figure 29: HP power (P_GS_EH_EH_F_BT1 / 6 kW).....	60
Figure 30: Monthly COP for different HP-sizes (P_GS_EH_F_BT1)	61
Figure 31: Monthly energy supply HP for different HP-sizes (P_GS_EH_F_BT1)	62
Figure 32: Monthly energy supply BUH for different HP-sizes (P_GS_EH_F_BT1).....	62
Figure 33: Duration curve delivered power for different HP-sizes	63
Figure 34: Monthly SPF for different HP-sizes (P_GS_EH_F_BT1)	64
Figure 35: Cost dependant on HP coverage factor (Z_GS_Gas_F_BT1).....	65
Figure 36: Cost comparison (Småland, 2013)	65
Figure 37: Cost comparison different buildings	67
Figure 38: Duration curve energy supply for different building at OCF.....	68
Figure 39: Comparison different BUH-systems.....	69
Figure 40: Duration curve power supply for different BUH (6 kW).....	70
Figure 41: Cost comparison for different tank layouts.....	71
Figure 42: Annual electric power consumption for different tank layouts	72
Figure 43: Tank temperatures at different nodes one week (P_GS_EH_F_BT1).....	72
Figure 44 Tank temperatures at different nodes one week (P_GS_EH_F_BT2).....	73
Figure 45: Cost comparison different tank sizes	74
Figure 46: Total thermal losses for different tank sizes (P_GS_EH_F_BT1 / 40 kW).....	75
Figure 47: HP-mode for different tank sizes (P_GS_EH_F_BT1 / 40 kW).....	76
Figure 48: Duration curve energy supply for different tank sizes (P_GS_EH_F_BT1 / 40 kW)	76

Figure 49: Cost comparison different tank control systems	77
Figure 50: Duration curve power supply of the heating-tank for different tank control systems (40 kW)	78
Figure 51: Cost comparison for different emission systems	79
Figure 52: Tank temperatures at the top for different emission systems.....	80
Figure 53: Duration curve power supply of the heating-tank for different emission systems (40 kW).....	80
Figure 54: Cost comparison for different ground temperatures	81
Figure 55: Monthly inlet temperature at the cold side of the HP for different ground temperatures (P_GS_EH_F_BT1 / 40 kW).....	82
Figure 56: Monthly COP / SPF for different ground temperatures (P_GS_EH_F_BT1 / 40 kW)	83
Figure 57: Cost comparison different profile for DHW-consumption	84
Figure 58: Duration curves power supply DHW-tank for different load profiles (P_GS_EH_F_BT1 / 40 kW).....	85
Figure 59: Cost comparison for different cost parameters	86
Figure 60: Progress of the work.....	94

Table of Tables

Table 1: List of abbreviations	7
Table 2: List of symbols	9
Table 3: Involved persons.....	19
Table 4: Critical review previous work	22
Table 5: Overview “Carnot toolbox”	25
Table 6: Summary equations operational cost.....	28
Table 7: Emission factors for different energy carriers.....	29
Table 8: Overview system combinations.....	31
Table 9: Summary HP’s used in the simulation tool.....	35
Table 10: Parameters buffer tank 1	39
Table 11: Parameters buffer tank 2	40
Table 12: Block definition emission system.....	46
Table 13: Internal loads.....	50
Table 14: Further work.....	92

Table of Equations

Equation 1: Cost el. energy HP	28
Equation 2: Cost el. energy pumps	28
Equation 3: Cost energy BUH.....	28
Equation 4. Maintenance cost HP	28
Equation 5: Maintenance cost BUH.....	28
Equation 6: Annual investment cost per component.....	29
Equation 7: Annuity factor per component	29
Equation 8: Outlet temperature BUH.....	42
Equation 9: Mass flow DHW	43
Equation 10: Control signal pump.....	46
Equation 11: Energy balance emission system	48
Equation 12: System temperature	48
Equation 13: Outlet temperature heating system.....	48

1 Introduction

In the past 30 years the world's CO₂ emission has doubled, this is reflected in the higher energy consumption during this period. These emissions can be reduced by using renewable energy or by lowering energy consumption. The residential sector has a huge potential to lower the consumption. Since this sector represents 27% of the global energy consumption and 17% of the global CO₂ emissions (Nejat, 2014). A result of these circumstances is the Zero Emission Building (ZEB).

The ZEB concept wants to bring the annual CO₂ emissions to zero by reducing energy consumption and being self-sufficient by producing its own energy. The use of heat pumps (HP) is a really interesting possibility to save energy; therefore the International Energy Agency (IEA) has formed a Heat Pump Programme in which it recommends the use of HP's and HP related technologies. The work done during this project is participating in the latest Program called the IEA HPP Annex 40 "Heat Pumps for Zero-Energy Buildings".

The goal of the project work is to analyse the change in design procedures of HP systems during the progressive improvement of the performance of energy building, i.e. starting from the standard performance of today, to the passive house standard and, finally, to the ZEB level. This will be done by using simple modelling approaches implemented in Matlab combined with Matlab/Simulink. This proposal is the continuation of a previous work by a Master student in the academic year 2012-2013. The present work will further improve the system modelling and the procedure of analysing results. Simultaneously, other techniques will be examined in detail, such as the impact of energy storage (e.g. storage tank, or storage in the ground when using ground-source heat pump).

1.1 Method

At the beginning of the project a research plan was set up. This paper includes main- and sub-goals, milestones and a timetable, and also sets guidelines for the further approach during the project. Various people were available to discuss the progress and the open tasks during the whole project.

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Table 3: Involved persons

1.1.1 Main goal

The main goal of this project work is to improve the model of a master student's work of the academic year 2012-2013. The principal parts that will be examined are listed below.

- Emission subsystem
- Distribution subsystem
- Storage subsystem
- Generation subsystem

The final simulation model has to include those improvements as well as a cost- and CO₂-emission analysis.

1.1.2 Sub-goals

The main goal contains different sub-goals which will be pursued during the project. These sub-goals are listed below.

1. Research plan including timetable for the project
2. Election of an alternative simulation platform to implement improvements
3. Selection of the system combinations that will be used for the SimTool

4. Elaboration of an improved simulation model
5. Sensitive analysis of the heat pump performance
6. Propositions for the future work
7. Scientific paper containing the main results of the work

1.2 Thesis structure

Chapter 2: This chapter includes a critical review on the previous simulation tool, these results were used to choose the software and set an algorithm for the simulation tool. The implementation of the cost and emission is also shown in this chapter.

Chapter 3: Describes the whole heating system, which is implemented in the SimTool. It starts by giving an overview of all the different system combinations and then an in-depth explanation of the different components used to build up those systems.

Chapter 4: The results of the different simulations with this tool are shown in this chapter. A comparison is shown between the actual and the previous simulation tool; furthermore the influence of different parameters (e.g. Tank size, Ground temperature) is investigated in this chapter.

Chapter 5: The conclusions out of the analysis performed in chapter 4 are summarized and compared here. The main findings out of this paper are listed as well.

Chapter 6: The SimTool is not ready for the market yet, however all the improvements needed to be done on the SimTool are listed in this chapter.

Chapter 7: The last chapter includes a reflection on the work as well as a comparison between planned and real progress during the work.

2 Simulation tool

The primary work of this thesis was to build up an improved simulations model based on the results of the critical review of a previous thesis (Småland, 2013). The main points of improvement between the two simulation tools are the storage system, the HP, the system control and the GSM. These changes in the model allow the user to do deeper research on the performance of the whole system as well as the influence of different parameters on the whole building system. The simulation tool is based on Matlab and Matlab/Simulink, the fact that they have the same base program allows an efficient connection between the two models. During the project the combination of Matlab and Modelica was investigated as an alternative variation. Since there is no official definition of the Zero Emission Buildings (ZEB), the definition taken for this thesis is copied from the previous thesis. “A non-residential building where CO₂-emissions associated to energy use for room and ventilation heating, as well as for air conditioning, room cooling (HVAC) and domestic hot water (DHW) is counterbalanced by on-site energy production on an annual basis.” (Småland, 2013)

The SimTool allows the user to investigate all different non-residential buildings by simply changing the input parameters. There is also the possibility to change the main system parameters directly from the Matlab. As a result of the simulations there are different comparisons between the cost and the emissions as well as the performance parameters (e.g. temperatures, power requirement, COP, runtime) available.

2.1 Review previous tool

The previous tool is a completely Matlab based tool, which allows the researcher to get an overview of the performance of the building heating system including a HP. It is also able to handle various input data. This allows for the possibility to investigate all different types of non-residential buildings. The results of the simulations were compared with the common rule of thumb and they were in an acceptable range. However, there are a lot of uncertainties in the whole model because the results of this research have to be reviewed by further simulations. Some points are simplified or not implemented, these points are listed below.

Field of improvement	Summary
Buffer tank	There is no buffer tank implemented in the simulation tool, so the user is not able to see the impact of this component.
HP model	<p>The coefficient of performance (COP) is a fixed value, in this way the HP performance is not affected by the different working temperatures.</p> <p>There is just an on/off HP-model implemented, the results with a various speed HP-model would be interesting.</p>
Free- / HP-cooling	There is a simplified cooling system implemented, this should be improved and connected with the GSM.
Ground source model	The GSM is too simplified and does not take into account the loading of the ground.
Auxiliary energy	Just the main pumps and ventilations systems are taken into account.
Domestic hot water	The domestic hot water (DHW) production is done in an external optimisation loop and is not integrated in the system.
Hydraulic system	<p>The hydraulic system is not implemented, which means that the influence of one component by another one can't be seen.</p> <p>The hydraulic components are calculated without any pressure drop or heat lost in the whole system.</p>
Default values	All the default values have a big uncertainty and need to be proven.
Backup System	The backup system is always covering the whole heating requirement; sometimes a smaller system can be used.
Input Data SIMIEN	The data from SIMIEN need to be transformed every time before they can be used for the simulation.

Table 4: Critical review previous work

Nevertheless a lot of information and procedures can be removed from this work and implemented in the new model. By taking the same default values as for the previous model a comparison between the results is possible. It is therefore recommended to take the same values.

Some rules of thumb for the installation of HP in Norway are listed below; these rules can be used to verify the results of the simulations (Småland, 2013).

- About 40-70 % HP power coverage factor gives 70-90 % energy coverage for air source heat pumps (ASHP) in different climate zones in Norway.
- Use a “cheap” peak power system in combination with HP base load.
- The total annual cost curve (ref. Figure 1) is relative “wide” and symmetric near the optimum.
- Ground source heat pumps (GSHP) should have higher energy coverage than ASHPs.

2.2 Software

To implement the new aspects of the simulation the choice of another simulation platform was recommended. Since there are several software-systems available, where the various components are already implemented, a comparison and selection of the optimal platform was done first.

In agreement with the supervisor the focus was set to be not just on Modelica and TRNSYS as mentioned in the master task. Like this it is possible to compare multiple programs and to choose the best one for this task.

2.2.1 Selection

Market research has found three strong programs, which are being widely used in this field already. The advantages and disadvantages of the different tools are listed below.

Modelica/Dymola

+ Modelica building library (Library with storage systems, some simplified borehole models)

- + TIL-Library (heat pump models included)
- + FMI (Functional Mockup Interface to import blocks in Matlab / Simulink)
- Can't have Matlab as executing program just coupling possible
- TIL-Library is a paying library

TRNSYS

- + Various emission-, distribution- and boiler-systems which can easily be improved
- + Detailed tank models
- No pressure drop in the distribution system
- HP and GSM are only models to buy
- Can't have Matlab as executing program just coupling possible

Matlab/Simulink “Carnot Toolbox”

- + Various emission-, distribution-, boiler - systems
- + Detailed tank models
- + Pressure drop and heat lost in the components and the pipes possible
- + Library is available free of charge
- + Coupling with / executing from Matlab without problems
- No advanced HP model (just on/off HP)

Technically it should be possible to construct the new model with all the three systems. In Modelica, especially the TIL-library seems to be strong on the HP side of the model where TRNSYS is more commonly used for building simulations. The “Carnot toolbox” has two main advantages. First the executing of the whole simulation can be done easily from Matlab. Second, the toolbox is freeware with a big user community working on improving the models. Also the fact that it is Matlab/Simulink resp. Matlab based makes it easier for fellow students to work with it. Master's students should be acquainted with these systems. The main disadvantage of not having an advanced HP model in the “Carnot toolbox” can be dissolved by using the Functional Mockup Interface (FMI). This interface allows the user to create advanced HP models in Modelica and to import them as a block into Matlab/Simulink.

2.2.2 Carnot toolbox

The “Carnot toolbox”, as mentioned earlier, is available free of charge and just requires an installation of the normal Matlab including Simulink. The Simulink toolbox was set up and is provided by the Solar Institut Jülich in Germany, and where one can obtain the toolbox too. The toolbox is aimed for easy design, analysis and simulation of models of energy system for use both in the conventional field and also in the field of regenerative systems, with components like solar collectors. The combination of Matlab’s mathematical features and Simulink’s simple block diagram interface makes it a powerful tool for all engineers involved in the field of house heating (Hafner, 1999).

The toolbox consists of blocks in which the different physical models are implemented. Inside the block there are either Simulink blocks or S-functions used to reproduce physics. The S-functions refers to an m-file with the code in it, this way it is easily possible to change or modify the blocks. The different sub libraries and the main blocks they have inside are listed in the table below.

Sub library	Components
Basic	Material Properties, Hydraulics, Pressure drop, Thermal models, Weather and sun
Control	Sensors, Controller, Energy meters
Hydraulics	Valves, Mixers, Diverters, Pumps, Pipes
Load	Electric, General, Houses, Hot water tapping
Outputs	THB-, THV-, Weather-selectors
Storage	Ground storage, Water storage
Source	Boiler, Chiller, Heat pump, Heat exchanger, Solar thermal, Electric generator
Toolbox	System functions, Utility blocks
Weather	Weather blocks, Collector positioning

Table 5: Overview “Carnot toolbox”

2.2.3 Functional Mockup Interface

Several studies show that a various speed HP can increase the performance of the building heating system. Therefore it is beneficial to have such a model implemented in the simulation tool. Since there is no such model available in the “Carnot toolbox”, another way to provide this model needs to be found.

The Functional Mockup Interface (FMI) allows the user to pass models between different simulation programs (e.g. Matlab/Simulink – Modelica) by creating so called Functional Mockup Units (FMU). Regarding this project, the FMI gives the possibility to build advanced HP model in Modelica and after converting it into an FMU it can be used as a normal block in Matlab Simulink. To transfer the model from one software to another a special FMI-Tool as well as the FMI inserts for the simulation programs are required. During the project work the FMI Suite (FMI Suite, 2010) from TLK-Thermo was tested to transfer the models between Modelica and Matlab/Simulink. The main points of the workflow with this FMI Suite are described below.

- Create advanced heat pump model in Modelica therefore it is recommended to use the TIL-Library and some knowledge in using Modelica is required.
- Set input and output variables in the Modelica model, these parameters will be displayed as ports on the Simulink block.
- Convert the Modelica model to a FMU by using the FMI-insert for Modelica.
- Import the FMU to Matlab/Simulink by using the FMI-Insert for Matlab/Simulink. This will create a Simulink block with the defined input and output ports which can be connected to the different signals in Matlab/Simulink.

As soon as the model is converted into a FMU the creating software (in this case Modelica) is not used anymore. The FMU just requires the FMI-insert for the new software (in this case Matlab/Simulink) to run the model.

2.3 Algorithm

The SimTool works on Matlab and Matlab/Simulink. The way in which the two systems are combined is showed and described below.

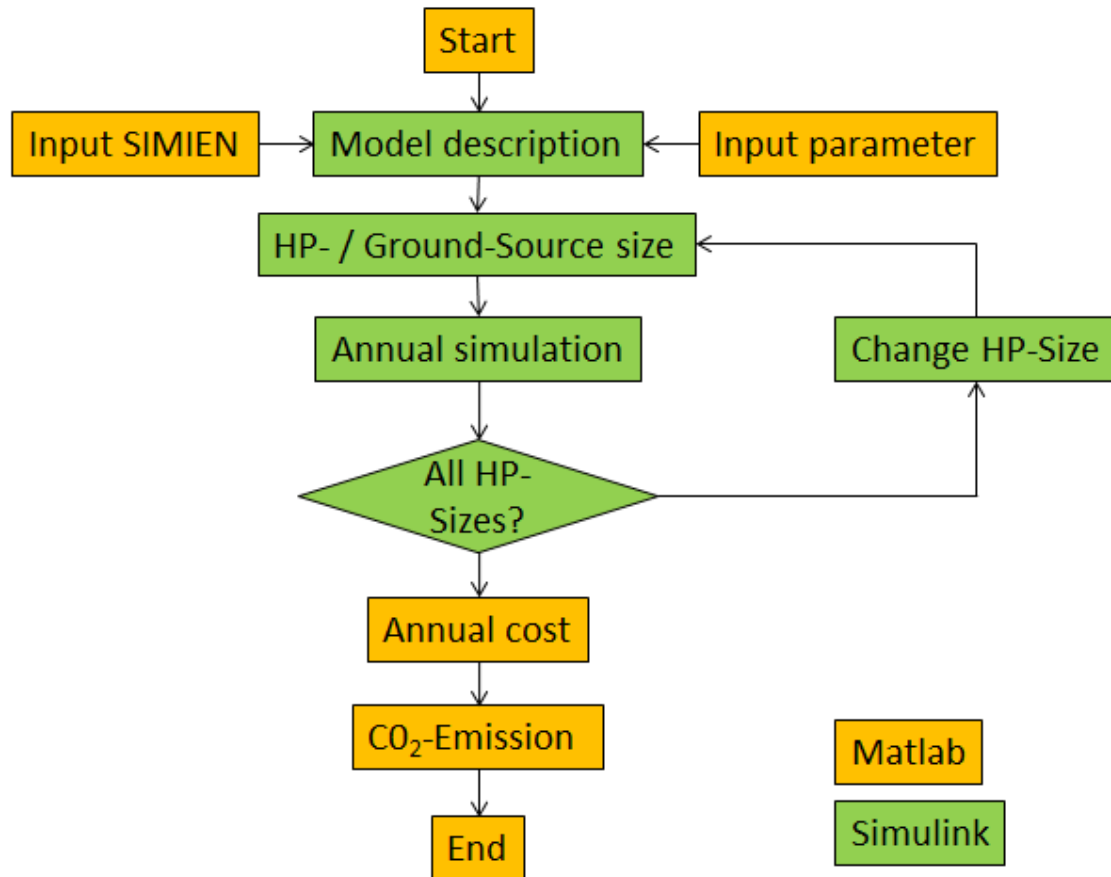


Figure 1: Simulation algorithm

The Matlab is mainly used to execute simulations and to handle input and output data; the building system itself is implemented in Simulink by using the “Carnot toolbox”. As shown in the Figure 1 the simulation is started from Matlab where the input parameters have to be defined as well. All this information is then transferred to the Simulink model, which will run the annual simulation of the building heating system. To investigate the influence of different coverage factors the size of the HP is changed for the same model configurations and the annual simulation starts again. This continues until all the different HP-sizes are simulated. By using the “Parallel Toolbox” from Matlab the repeating sequence can be examined in parallel. As soon as all the annual simulations are done and the results transferred to Matlab, where the annual costs and CO₂ emissions are calculated.

2.4 Cost implementation

As shown under the description of the algorithm, the costs are calculated in Matlab after the whole simulation is finished. The output file from Simulink includes information about the power requirement of each component; this chapter shows how they are used to calculate the costs for the different systems.

The total costs can be divided into two main categories. There are operational costs on one side and the investment costs on the other side; the total cost for the system is just the sum of those two components.

2.4.1 Operational costs

The operational costs are the costs needed to run all the different components as well as the costs for the maintenance of the different components. The table below shows the calculation of the different components (Småland, 2013).

Costs	Component	Equation
Energy	El. energy HP	$C_{op.HP} = P_{el.HP} * c_{el}$ <p style="text-align: center;">Equation 1: Cost el. energy HP</p>
	El. energy Pumps	$C_{op.Pump} = \sum P_{el.Pump} * c_{el}$ <p style="text-align: center;">Equation 2: Cost el. energy pumps</p>
	Energy BUH	$C_{op.BUH} = (P_{el.BUH.DHW} + P_{el.BUH.Heat}) * c_{el}$ <p style="text-align: center;">Equation 3: Cost energy BUH</p>
Maintenance	HP including source	$C_{main.HP} = C_{inv.HP} * f_{main.HP}$ <p style="text-align: center;">Equation 4. Maintenance cost HP</p>
	Backup heater	$C_{main.BUH} = C_{inv.BUH} * f_{main.BUH}$ <p style="text-align: center;">Equation 5: Maintenance cost BUH</p>

Table 6: Summary equations operational cost

2.4.2 Annual investment cost

The annual investment costs are calculated using the annuity factor, which depends on the interest rate and the expected lifetime of the component (Småland, 2013).

$$C_{ann.inv} = I_{comp} * a_{comp}$$

Equation 6: Annual investment cost per component

$$a_{comp} = \frac{ir}{((1 - r)^{n_{comp}} - 1)} + ir$$

Equation 7: Annuity factor per component

As you can see in the equation the interest rate is set to be the same for all the different components, so the change of the annuity factor for the different systems is due to the change in the expected lifetime of the components.

To calculate the total annual investment cost, the main components which are listed below were taken into account.

- HP including GSM
- BUH for both tanks
- Emission system (Floor heating or radiators)
- DHW-tank and heating-tank
- PV-panels (just for ZEB)

2.5 Emission implementation

The CO₂ emissions are directly linked to the energy consumption, for each energy carrier there is a different emission factor (Småland, 2013).

Energy carrier	Emission factor
Electricity	395 g/kWh
Bio mass	42 g/kWh
Natural gas	211 g/kWh

Table 7: Emission factors for different energy carriers

3 System

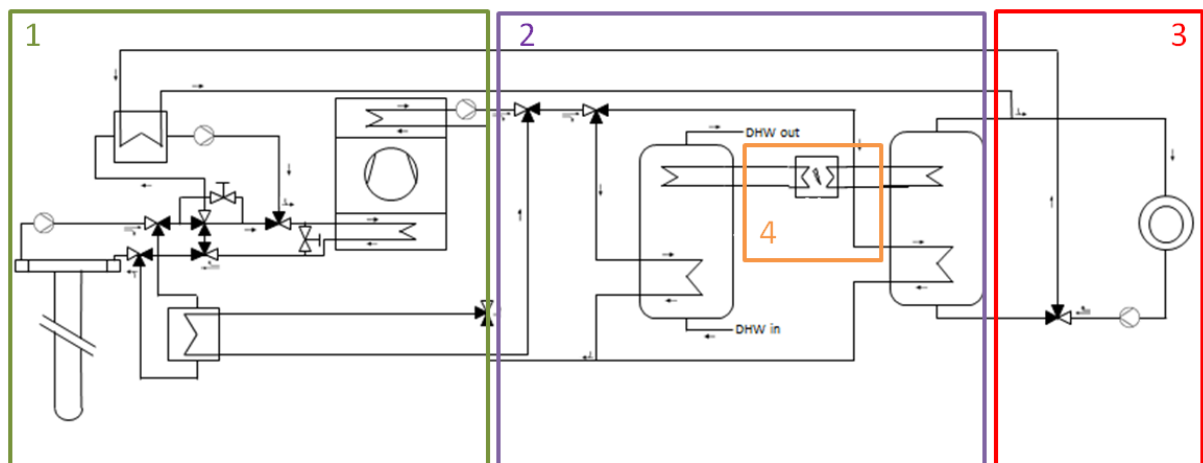
The SimTool investigates the building heating system for non-residential buildings on three different levels of building performance:

- TEK 10
- Passive house
- Zero emission building (ZEB)

The building itself is not included in the Simulink model, the loads for the different types of buildings are calculated in external software (SIMIEN) and then imported into the Simulink model. All the other components of the heating system are implemented in the Simulink model and described in this chapter.

3.1 System combinations

There are several system combinations implemented in the SimTool. Those combinations represent the state of art and were found by literature research (Dott, 2010).



1 – Source 2 – Distribution system 3 – Emission system 4 – Backup heating system

Figure 2: System boundaries

In order to simplify the overview of the different solutions, the building heating system is divided into four subsystems which are shown in Figure 2. In the Simulink model these subsystems can be exchanged and reassembled to create another system. The figure

above shows an example of a GSHP with an electric BUH and a floor heating system. This system is also used as a reference system during the whole thesis.

Boundary 1 / Source: This subsystem includes the main heat source of the BHS. The heating or cooling power produced here is transferred to the heating tanks or the cooling system. For the different coverage factors this is the only subsystem which is changed.

Boundary 2 / Distribution system: The heating- and the DHW- tank as well as the control system for the energy supply are located in this system. The control signals generated here are used to operate the HP resp. BUH and to set the valves in the right positions.

Boundary 3 / Emission system: This system represents the interface between the heating system and the building. It includes the radiators or floor heating as well as the DHW-consumption. There are several sensors which control the tank temperatures and the mass flow through the radiators.

Boundary 4 / Backup heating system: Three different types of backup heaters (BHU) are implemented in this simulation tool. To make sure that the tank is always able to deliver the needed heat there is one BUH per tank.

Source	Distribution system	Backup heating system	Emission system
GSHP	Tank system 1	Electric boiler	Floor heating
ASHP	Tank system 2	Bio boiler	Radiator heating
		Gas boiler	

Table 8: Overview system combinations

3.2 Components

In this chapter the physical model behind each component and which input parameters need to be set for each model are explained. Not all equations are listed in this chapter; primarily just the method behind the equation is explained. All the specific equations can be found in the Carnot help (Hafner, 1999). A summary of all the different input parameter is to be found in appendix 1.

The connection between the different blocks is done by a so called THB-Vector. This is a vector where all the hydraulic and thermal properties of the fluid are collected. In the Figure 3 the different parameters are shown.

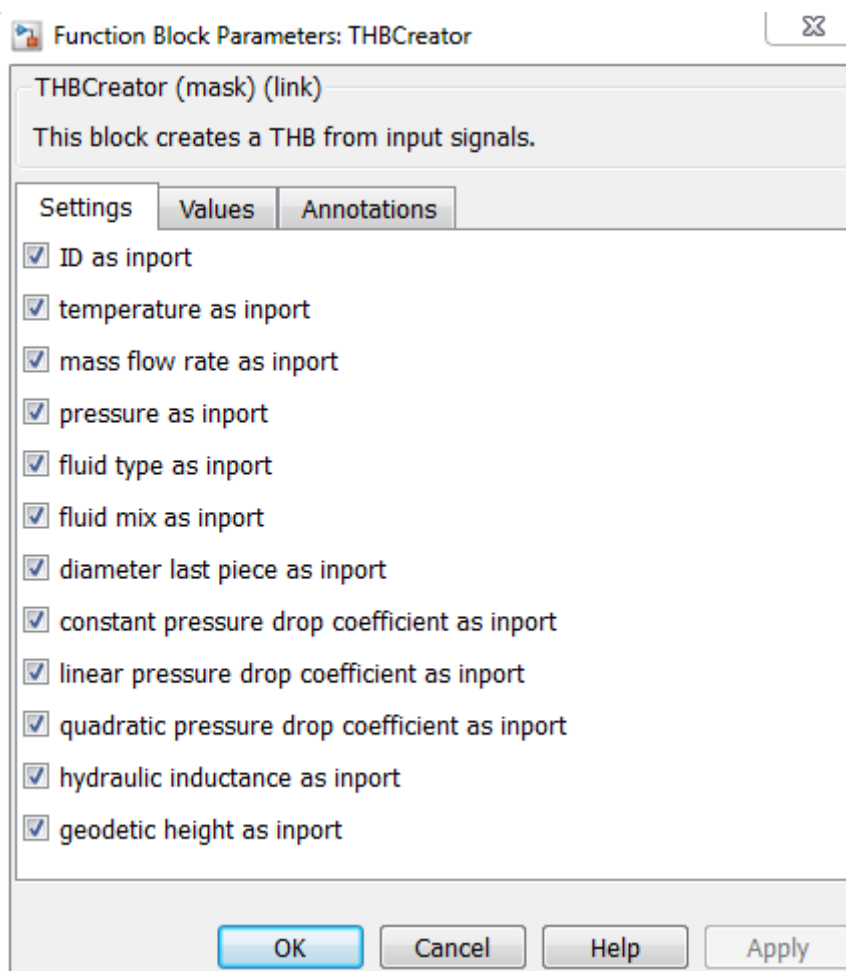


Figure 3: Parameters THB vector

3.2.1 Heat pump

As already mentioned, the “Carnot toolbox” just includes an on- off model of the HP. It is a linearized HP model which uses measured data according to EN14511 as input. The dynamic behaviour of the heat pump is calculated using an empirical model (Schwamberger 1991). The model is based on the static characteristics of the heat pump according to the German standard DIN 8900. In the two-dimensional diagram the heating power is given for different temperatures in the primary and secondary cycle. The model also includes thermal und hydraulic losses. The block requires temperature vectors, power matrices and the thermal and hydraulic coefficient as input. The temperature vectors and the power matrices can be found in characteristic curves for the heat pumps. The characteristic curves used during the thesis are shown in appendix 5. An example for an 11 kW GSHP is shown below.

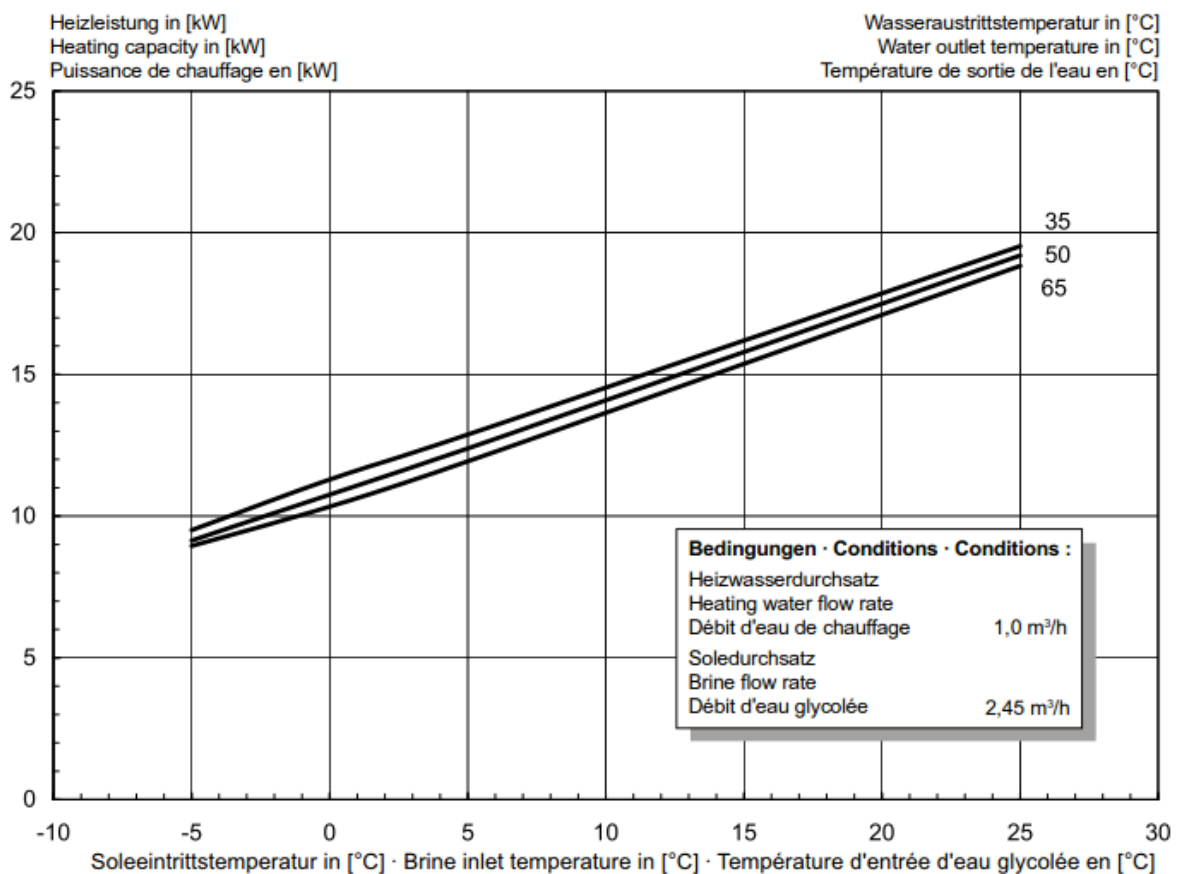


Figure 4: Characteristic curve 11kW GSHP

Using this example the following vectors and matrix can be created:

Temperature vectors

$$T_{inlet.Source} = \begin{pmatrix} -5 \\ 15 \\ 25 \end{pmatrix} \quad T_{outlet.Load} = \begin{pmatrix} 35 \\ 50 \\ 65 \end{pmatrix}$$

Heating power matrix

$$Q_{Source} = \begin{pmatrix} 9500 & 9100 & 9000 \\ 16200 & 15800 & 15400 \\ 19540 & 19210 & 18830 \end{pmatrix}$$

Depending on which building is used for the simulation, there are different HP used, the table below gives an overview over all the HP's used in the simulation.

Nr.	Coverage factor [%]	HP- Size [kW]	BH –length [m]
GSHP / Passive building			
6	100	75	5000
5	66.7	50	3333
4	53.3	40	2667
3	26.7	20	1333
2	14.7	11	733
1	8	6	400
GSHP / TEK 10			
6	100	130	8667
5	80.0	100	6667
4	57.7	75	5000
3	38.5	50	3333
2	30.8	40	2667
1	15.4	20	1333

ASHP / Passive building			
6	75	54	-
5	62.5	45	-
4	50	36	-
3	37.5	27	-
2	25	18	-
1	12.5	9	-

Table 9: Summary HP's used in the simulation tool

For all the GSHP's it was possible to find characteristic curves in all the different HP-Sizes, the datasheets are collected in the appendix 5. For the ASHP there wasn't that much information available so the values for the missing sizes were found by interpolating the given characteristic curve.

3.2.1.1 Heat pump modes GSHP

The GSHP can be used to heat up the two buffer tanks or to run the forced cooling. The hydraulic realisation of this switch between the modes is described in this section

Heating mode

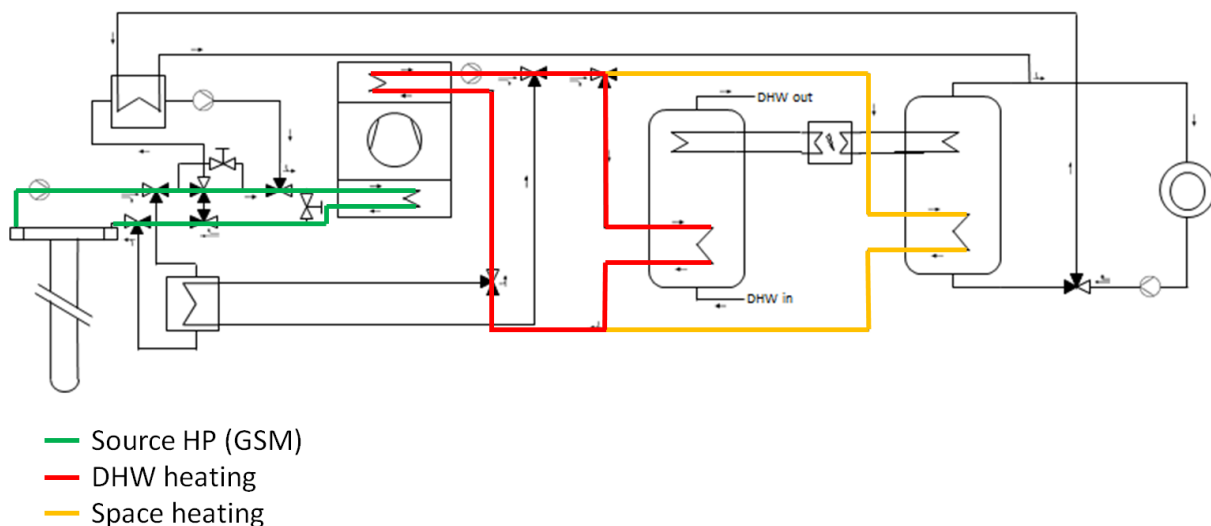


Figure 5: Layout heating mode GSHP

The heating mode is the most used mode of the HP; hence the cold side of the HP is directly connected to GSM (green). The hot side of the HP is connected either to the

domestic hot water tank (DHW-tank) (red) or the heating tank (orange), depending on which tank needs to be recharged; the priority therefore is on heating up the DHW-tank.

Free cooling mode

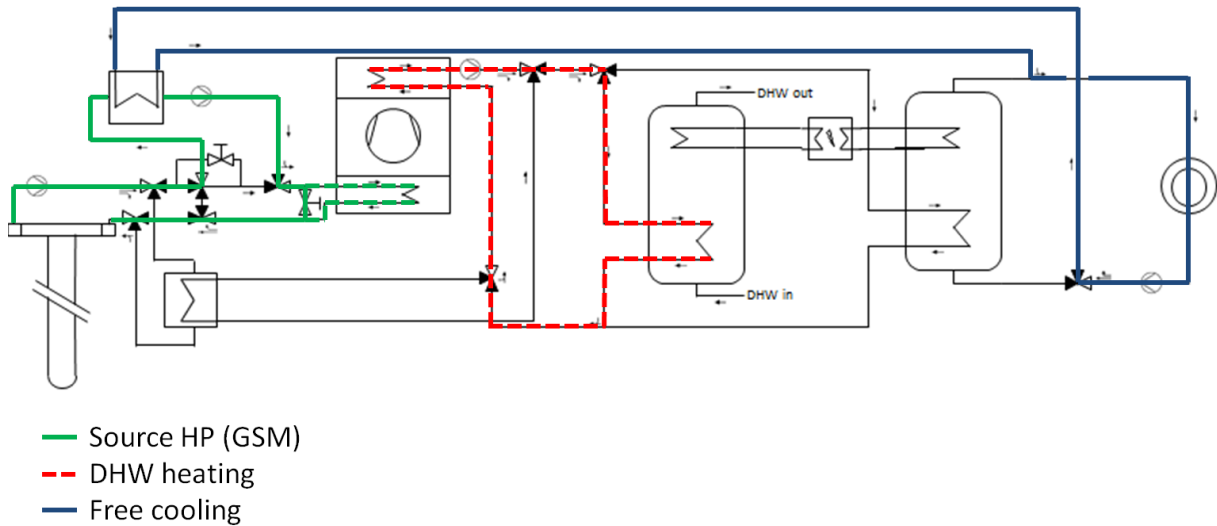


Figure 6: Layout free cooling mode GSHP

The cooling potential of the ground is used in the free cooling mode. Through a heat exchanger the back flow of the emissions system (blue) is connected to the GSM (green). If DHW is needed at the same time, the valves will connect the cold side of the HP to the GSM (green dotted) and the HP is then able to heat up the DHW tank (red dotted).

Forced cooling mode

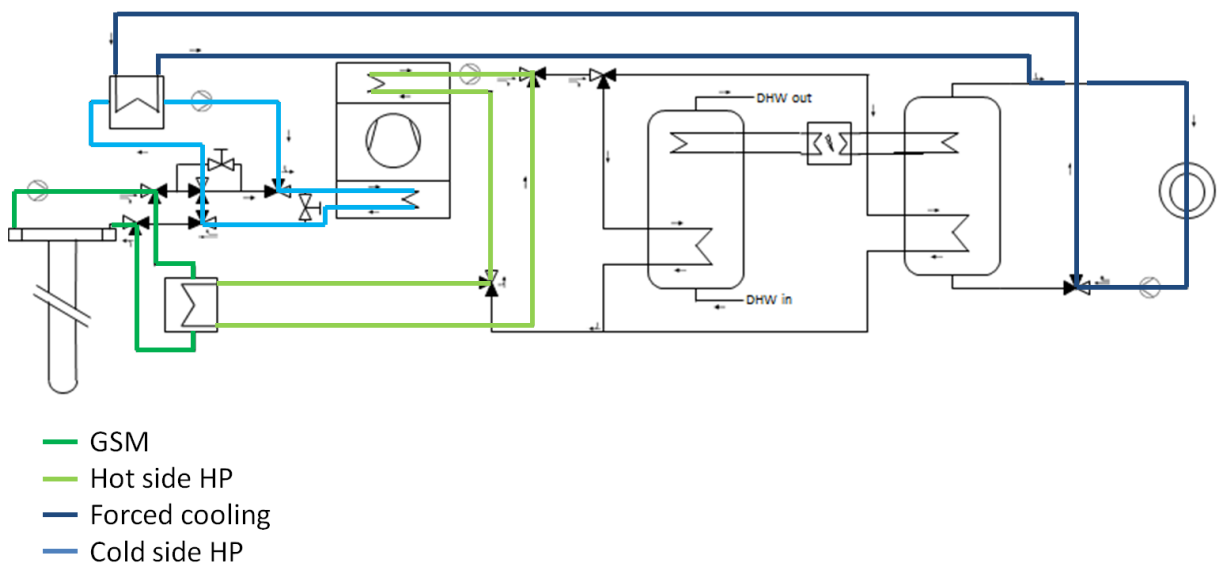


Figure 7: Layout forced cooling mode GSHP

If the cooling load is too high to be cooled by free cooling the forced cooling mode starts. In this case the HP is used as a chiller; this is simply done by changing hot and cold side of the HP by some valves. The emission system is then connected over a heat exchanger (HE) to the HP and represents the cold side of the HP (blue). The GSM is then connected to the hot side, requiring another heat exchanger between the two cycles (green).

3.2.1.2 Heat pump modes ASHP

Using an ASHP the system looks different since there is no possibility of free cooling. In this simulation tool a HP with a 4-way valve, which allows switching between heating and cooling mode in the HP itself, is implemented. As there is no such model available in the Carnot library, two HP's of the same size are used to implement it to Simulink. At one HP the outdoor air is connected on the hot side, on the other HP the outdoor air is connected to the cold side. The control of the HP is done in a way that there is always just one HP running at any given time.

Heating mode

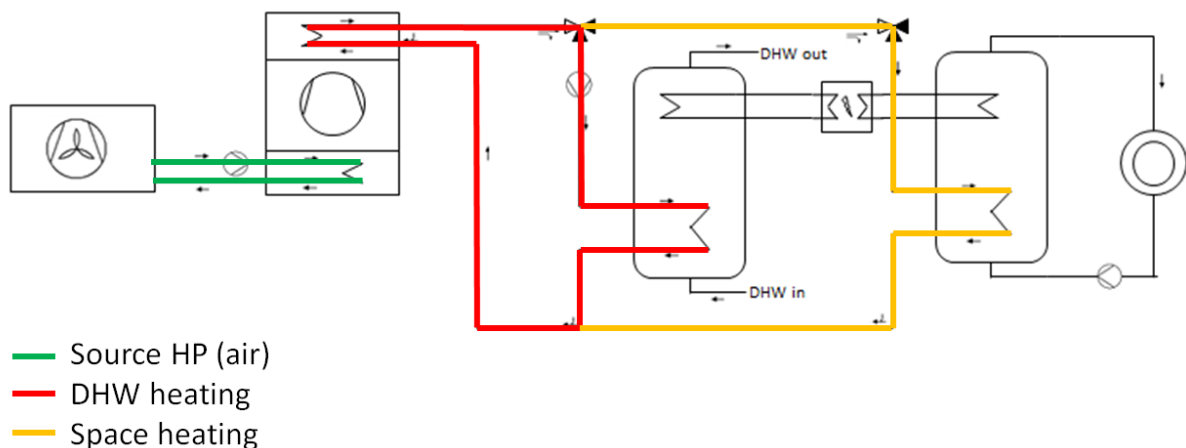


Figure 8: Layout heating mode ASHP

The heating mode for the ASHP works quite similarly to the GSHP, on the cold side there is a ventilator, which brings the air to the cold side of the HP (green). On the hot side the HP is either works on the DHW –tank (red) or on the heating tank (orange). The priority here is on the DHW-tank as well.

Cooling mode

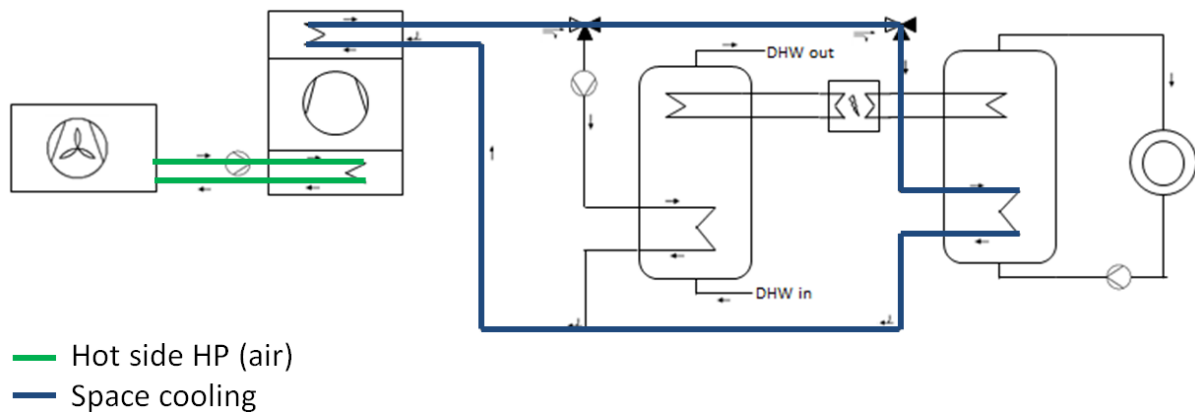


Figure 9: Layout cooling mode ASHP

For the cooling period the buffer tank, which is connected with the emission system, is cooled down by using the HP as a chiller (blue). During the cooling period the priority for the HP is to cool this tank down. If heating power is needed for the DHW tank during this period it is delivered by the BUH.

3.2.2 Tank

The model divides the tank into nodes on both fluid sides; the heat transfer side and the outer wall. The energy balance for every node is solved using the differential equation. The model allows the user to modify the size of the tank or the position of the in-, and outlet. It is also possible to change the heat exchangers implemented in the tank.

This model gives the possibility to investigate different tank layouts and sizes. All these settings which were investigated during this thesis are listed below.

3.2.2.1 Buffer tank 1

This tank includes three different in- and outputs where the loads are connected. For the connection to the loading systems (HP, BUH) pipe heat exchangers according to EN12977 are implemented. The DHW- or heating water is heated in a flow through principle, which means that the water in the storage tank is directly used for consumption. A temperature sensor, which controls the HP and BUH, is also placed in this model. The sketch shows a rough overview of the whole system, and in the table below the most important parameters are listed.

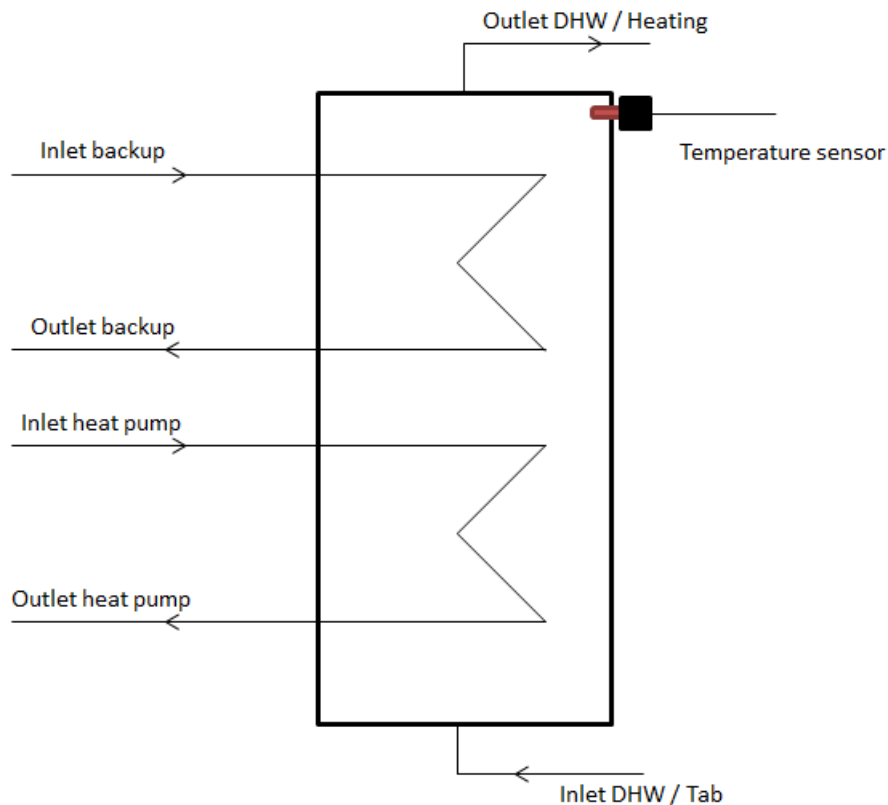


Figure 10: Sketch buffer tank 1

The height is measured relative to the total height of the tank, where 0 is at the bottom and 1 is at the top of the tank.

System	Connection	Relative height [-]
Heat pump	Inlet	0.7
	Outlet	0
Backup heater	Inlet	1
	Outlet	0.7
DHW-, Heating system	Inlet	0
	Outlet	1
Control	Temperature sensor	1

Table 10: Parameters buffer tank 1

3.2.2.2 Buffer Tank 2

This tank includes the same components like the BT1; just the positions off the connections are different. These changes are shown in the sketch and tables below.

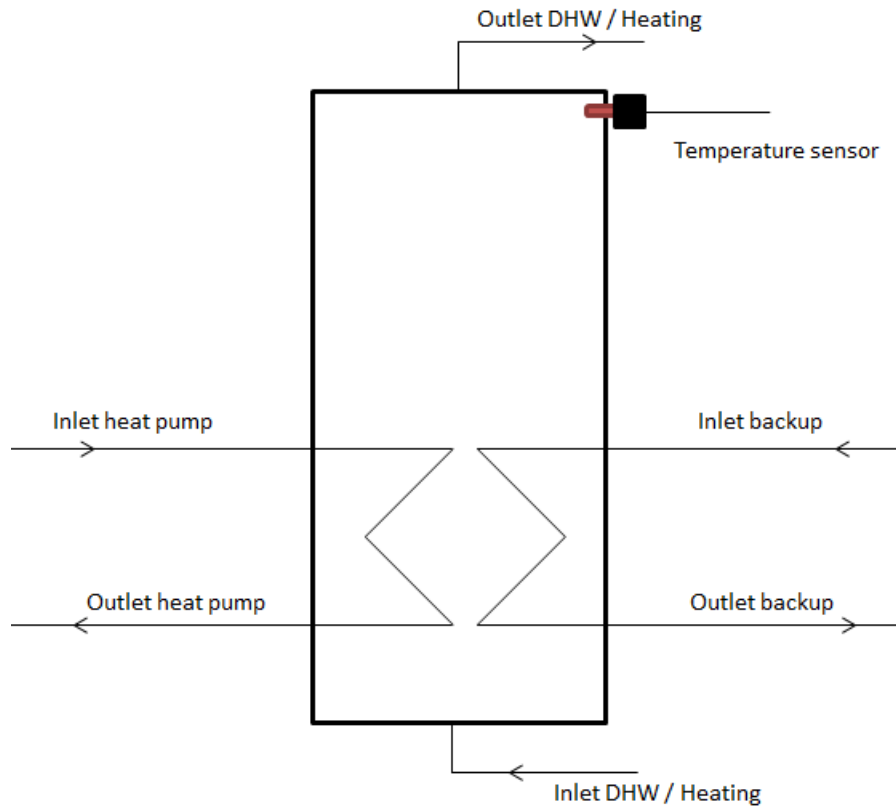


Figure 11: Sketch buffer tank 2

System	Connection	Relative height [-]
Heat pump	Inlet	0.5
	Outlet	0
Backup heater	Inlet	0,5
	Outlet	0
DHW-, Heating system	Inlet	0
	Outlet	1
Control	Temperature sensor	1

Table 11: Parameters buffer tank 2

3.2.2.3 Control system

The temperature sensors, which are described below, are used to control the HP as well as the BUH. There are different control strategies for the DHW- and the heating-tank, the difference between those strategies is the set temperature at which the HP or the BUH starts and stops.

DHW-tank

The set temperature of the DHW-tank is defined by a repeating sequence, which raises the temperature over 60 °C once a week. This strategy is introduced to prevent the formation of legionellae in the tank. The set temperature to start the BUH is always 5 °C colder than the set temperature to start the heating pump. In this way the BUH always starts when the HP is unable to deliver enough power to the tank. The Figure below shows an example of this repeating sequence.

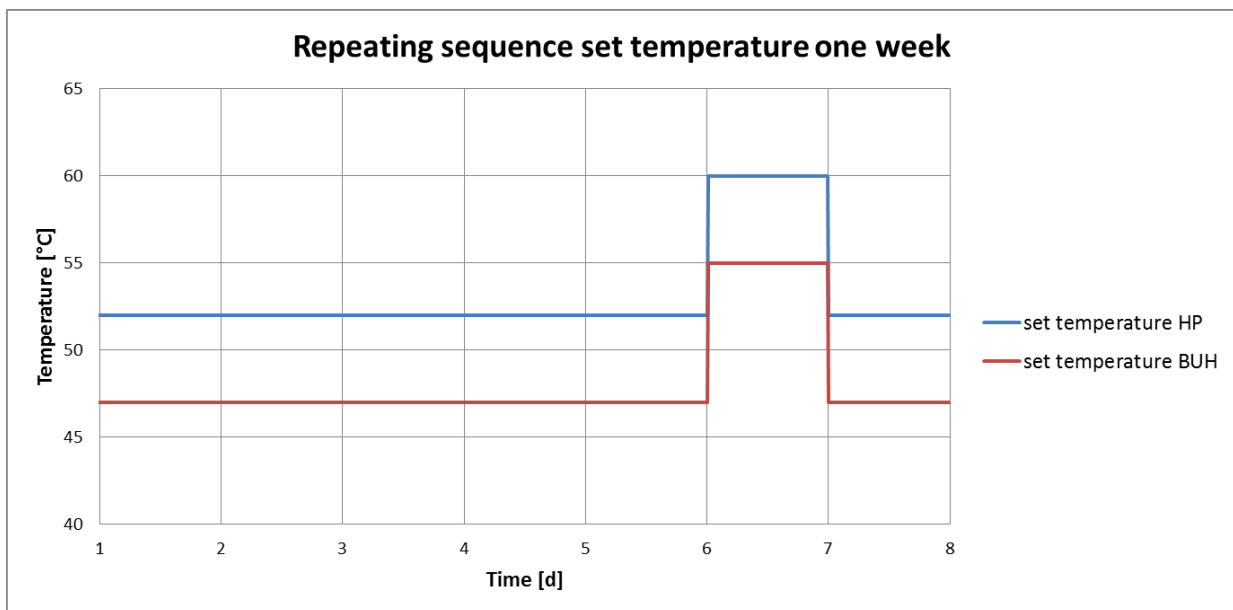


Figure 12: Repeating sequence set temperature

Heating-tank

Two different strategies for the heating tank are implemented in the models. In the first strategy the set temperature for the HP is always said to be 5 °C higher than the supply temperature needed for the heating system during the heating period (winter) and constant on 20 °C during the cooling period (summer). The second strategy sets a constant temperature of 45 °C for the winter and of 20 °C for the summer. The set

temperature to start the BUH is set in the same way as the DHW-tank, always 5 °C colder than the set temperature to start the HP.

Using an ASHP as a supplier, the buffer tank is used as a cold storage during summer. Due to this reason a set temperature of 12 °C during the cooling period is implemented and the BUH is not in use then.

3.2.3 Electric heater

The electric heater simply changes the temperature of the THB-vector entering the block according to the electric power.

$$T_{outlet} = T_{in} + \frac{P_{el.in}}{m_{in} * c_{p_{in}}}$$

Equation 8: Outlet temperature BUH

3.2.4 Bio boiler

The bio boiler is described by a furnace model, which considers only the constant nominal power transfer on the combustion chamber side of the furnace. On the water side of the furnace, a multinode model is used to model the time dependent conditions. The fuel, in this case wood pellets, is defined in a separate block. The parameters of the fuel are visible in the appendix 1.

3.2.5 Gas boiler

For the gas heater, the model is similar to the bio boiler; just the fuel is changed to natural gas. The parameters of this fuel are summarized in the appendix 1 as well.

3.2.6 Ground source

The so called EWS model is implemented in the Carnot toolbox. It is a transient model for dynamic simulations of borehole heat exchangers. The model is based on the equations described by Huber and has been implemented using the space model of Matlab/Simulink (Huber, 1997).

According to the size of the HP the length of the boreholes are changed for different coverage factors. The lengths used are summarized in section 3.2.1. For the assembling the “5x10 probes B/H=0.1” configurations were always used.

A fellow student, Mikkel Ytterhus, did some deeper research on this model and the code behind it. For this work here just some default, standard parameters have been used. The experience and the result of his work can be used for the further development of this tool.

3.2.7 Heat exchanger

The NTU-method is implemented in this heat exchanger model; furthermore the input temperatures are delayed by the heat capacity of the heat exchanger. There is also the possibility to choose between cross-, counter-, or parallel-flow heat exchangers.

For both heat exchangers implemented in this tool a counter flow heat exchanger is applied since they have a smaller temperature difference than the other types.

3.2.8 DHW mixer

The input data for the DHW consumption is a load profile which is shown and described in the next chapter. This load profile includes information about the power consumption of the DHW. To implement this consumption in the Simulink model a constant DHW outlet temperature of 45 °C was assumed and the mass flow of the DHW is then continuously adapted using the following equation.

$$\dot{m}_{DHW} = \frac{Q_{DHW}}{(T_{DHW.out} - T_{DHW.in}) * cp_{DHW} * \rho}$$

Equation 9: Mass flow DHW

The cp-value used in this equation is calculated for the mean temperature between inlet and outlet. In the mixing block a thermostatic valve is used to set the outlet temperature at 45 °C. The layout of this block and his function are shown below.

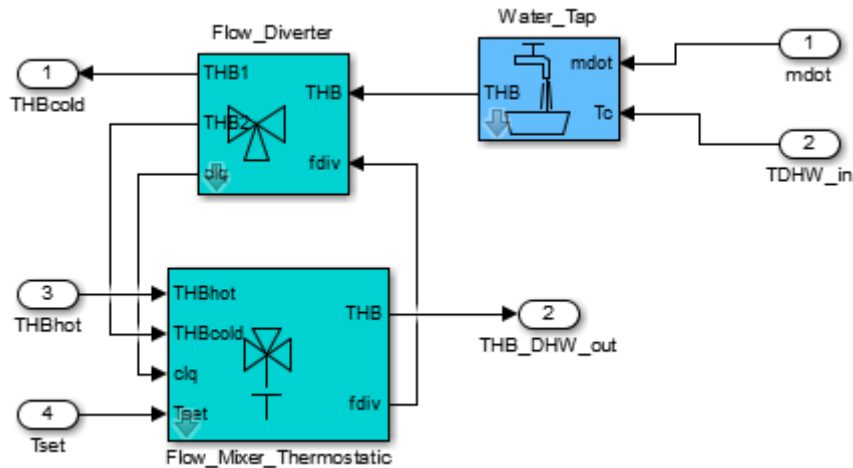


Figure 13: Layout DHW mixer

The block “Water_Tap” creates a THB vector with the DHW inlet temperature and the calculated DHW mass flow. The block “Flow_Mixer_Thermostatic” mixes the hot and the cold inlet (THBhot, THBcold) to the set temperature. It is done by controlling the “Flow_Diverter”. At that point, the flow either goes through outlet “THB1” to the DHW tank and comes back heated up through inlet “THBhot” or it goes directly to the mixer.

3.2.9 Emission system

The emission system is built up as a black box where the radiator or floor heating system is represented by the temperature requirement. An overview of the assembling and description of the function of the different blocks is shown below.

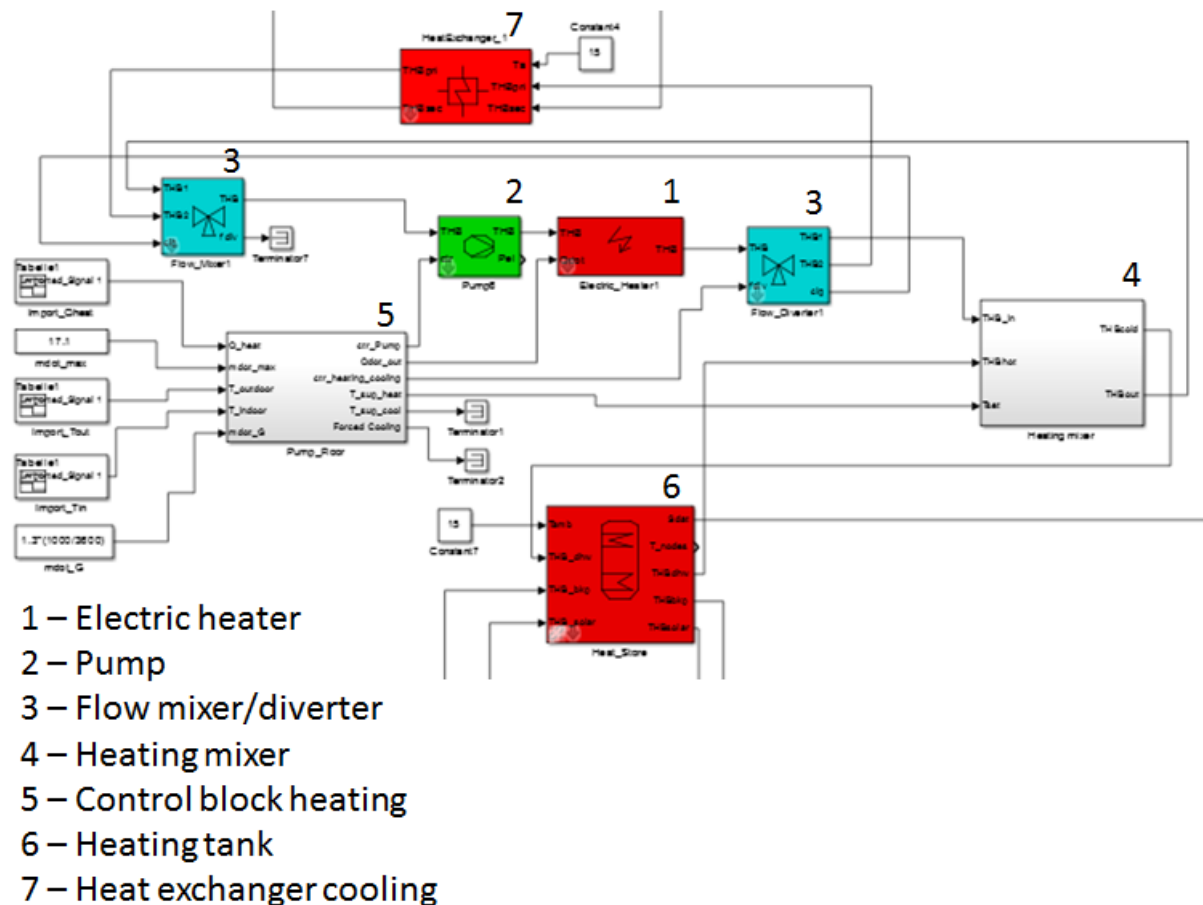


Figure 14: Layout emission system

In the main control block (No. 5) several equations, which control the whole emission system, are implemented. The inputs for this block are the values from SIMIEN; they are implemented as import signals and in this way the SIMIEN file is not used during the simulation. The electric heater (No. 1) represents the emission system; the flow enters with the set temperature here from the heating mixer (No. 4) and is heated or cooled (depending on the requirement) to the return temperature. The flow mixer and diverter (No. 3) switch between heating and cooling mode. In the heating mode the THB-vector is forwarded to the heating mixer (No. 4). Conversely, in the cooling mode the flow is guided to the heat exchanger (No. 7) which is connected to the ground source. The heating mixer (No. 4) works exactly in the same way as the DHW flow mixer described above. The mass flow of the heating system is controlled by the pump (No.2). The main block, where the equations are implemented is described below.

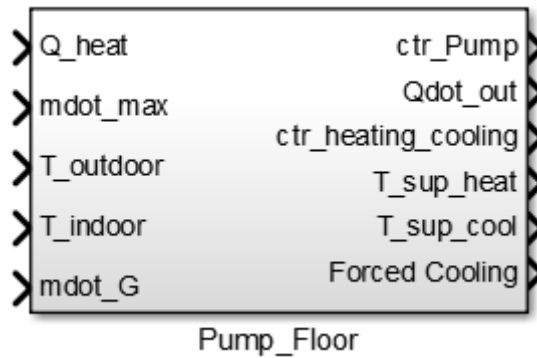


Figure 15: Control-block heating

Input		Output	
Nr.	Description	Nr.	Description
1	Heat requirement of the building (from SIMIEN)	1	Control signal for the pump between 0 and 1
2	Mass flow at highest heating requirement	2	Heating requirement to heating system
3	Outdoor temperature (from SIMIEN)	3	Signal to control heating and cooling mode 1 or 2
4	Indoor temperature (from SIMIEN)	4	Supply temperature heating mode
5	Mass flow on the ground source (HP-Data)	5	Supply temperature cooling mode
		6	Control forced cooling

Table 12: Block definition emission system

Control signal pump

$$ctrl_{pump} = \frac{\dot{m}_{max.heat}}{\frac{Q_{Heat}}{dT_{heat} * cp_{heat} * \rho}}$$

Equation 10: Control signal pump

This output is used to control the pump and thus adapts the mass flow of the heating system. The temperature dT_{heat} is the difference between supply and return temperature of the heating system, the calculation of these values is described below.

Heating requirement

This value is used as input for the electric heater which represents the emission system. It is arrived by multiplying the input value for the heat requirement by -1. This way the fluid gets colder at heating load and warmer at cooling load.

Signal heating-cooling mode

This signal is either one for heating mode or zero for cooling mode. When the heat requirement for SIMIEN is higher than zero it is one and if it is below zero it is set to zero.

Supply temperature heating mode

The supply temperature (inlet temperature of the heating system) depends on the outdoor temperature; therefore the so-called signature curves are introduced. The figure below shows an example of the signature curve for a floor heating system.

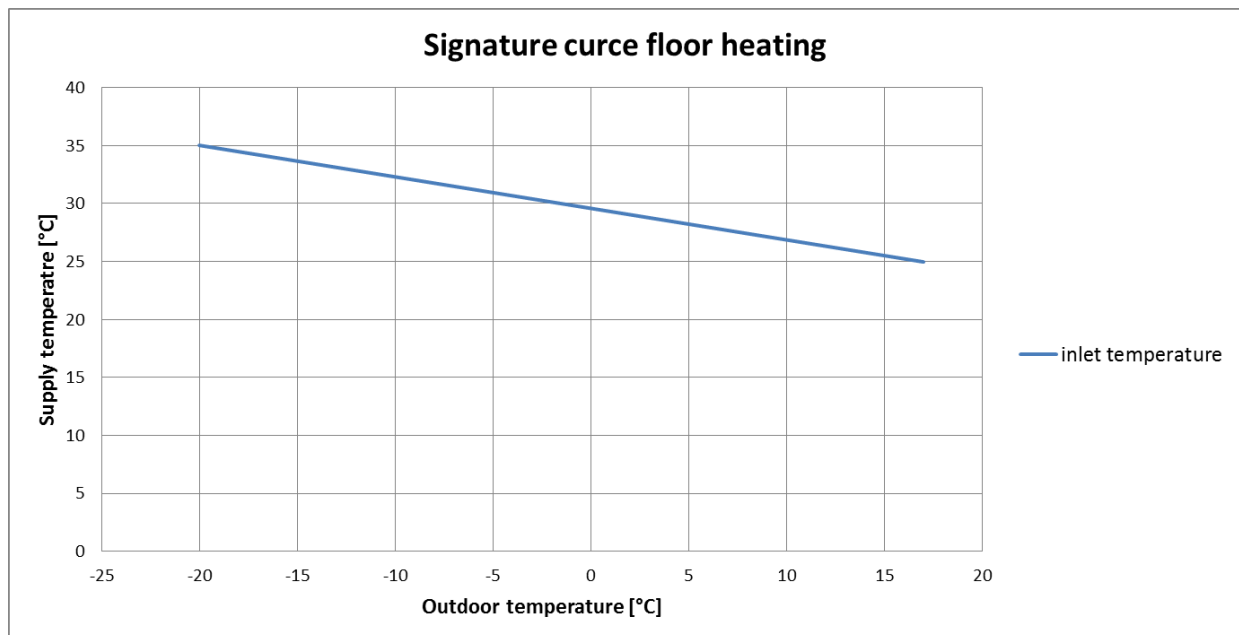


Figure 16: Signature curve floor heating

The return (outlet temperature of the heating system) depends on the outdoor temperature as well as the heating power; therefore the following equations are implemented in the simulation tool.

$$\frac{Q(t)}{Q_{nom}} = \left(\frac{\frac{U}{A} (T_s(t) - T_{room}(t))}{\frac{U}{A} (T_{s.nom} - T_{room.nom})} \right)^r$$

Equation 11: Energy balance emission system

This equation is the ratio between actual and nominal power. The heat transfer coefficient and the area can be dropped by assuming that they stay constant. The value r represents the radiator exponent.

$$T_s(t) = \frac{T_{in}(t) + T_{out}(t)}{2}$$

Equation 12: System temperature

This is a simple definition for the system temperature and it should be sufficient for this model. In this manner, a more complicated calculation using the logarithmic mean temperature difference (LMTD) can be avoided.

$$T_{out}(t) = 2 * \left(\left(\frac{Q(t)}{Q_{nom}} \right)^{\frac{1}{r}} * (T_{s.nom} - T_{room.nom}) + T_{room}(t) \right) - T_{in}(t)$$

Equation 13: Outlet temperature heating system

If the two equations above are combined and rearranged, the final equation for the outlet temperature of the emission system is reached. This equation is implemented in the Simulink model.

Supply temperature cooling mode

For the supply temperatures in the cooling mode the same approach, as shown above for the heating system, is used.

3.3 Loads

The loads implemented in this simulation tool can be divided into DHW loads and heating/cooling loads. These loads were evaluated for a benchmark building in another master's thesis (Smedegård, 2012) The building calculated there is a free standing office building without a basement, which is located in Oslo. The design, which is seen in the figure below, refers to the today's office building standard. The simulation of this building was done in SIMIEN by using the NS 3940.

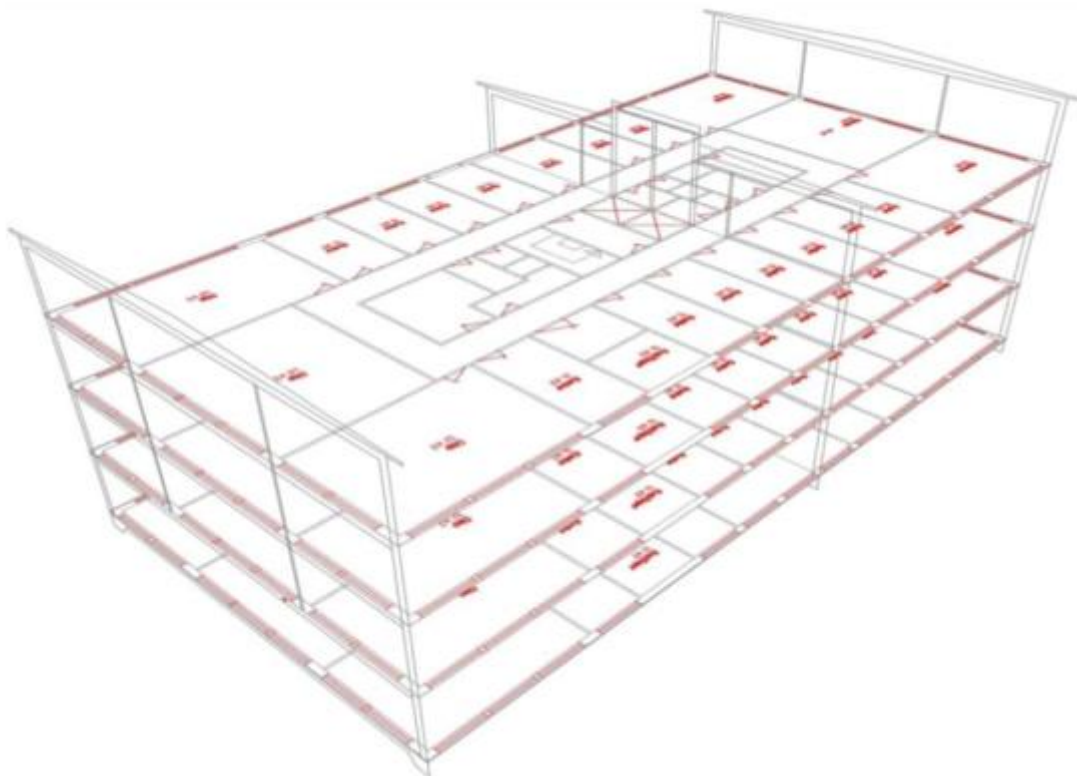


Figure 17: Design office building

Building parameters

As shown in the figure above the building has four stories, which have a height of 3.2 m each. The total heated area is 2400 m² the roof is 630 m² with a slope of 3%. The building has a high thermal mass and is classified as “heavy” according to the NS 3031. The building's core, which includes stairs, elevator shaft and the floor slabs, are made of concrete. The walls in between the offices are not loadbearing as they are made out of wood. Every floor has 42 windows, which represents altogether 20 % of the net area.

Solar shading

In the model high shading, due to structural canopy, external shading on the west, east and south facing facades, is introduced. This leads to low cooling loads for the building which is favourable for ZEB and passive houses.

Internal load

100% occupancy during the working weeks is taken into consideration, which is defined as a 5-day week with 12 hour days (NS 3031). The internal loads are defined according to NS 3031 (TEK10) and prNS3701 (ZEB, Passive house), they are listed in the table below.

Load	TEK 10 [W/m ²]	Passive house and ZEB [W/m ²]
Person loads	4	4
Lighting	6.4	4
Equipment	11	6

Table 13: Internal loads

3.3.1 Heating/cooling loads

The output file from SIMIEN includes information about the power requirement, the outdoor temperature and the indoor temperature. The time step of the data is one hour. These values were read in Matlab and then imported to the Simulink model as an imported signal. The figure below shows an example of the power requirement of a passive building for one year.

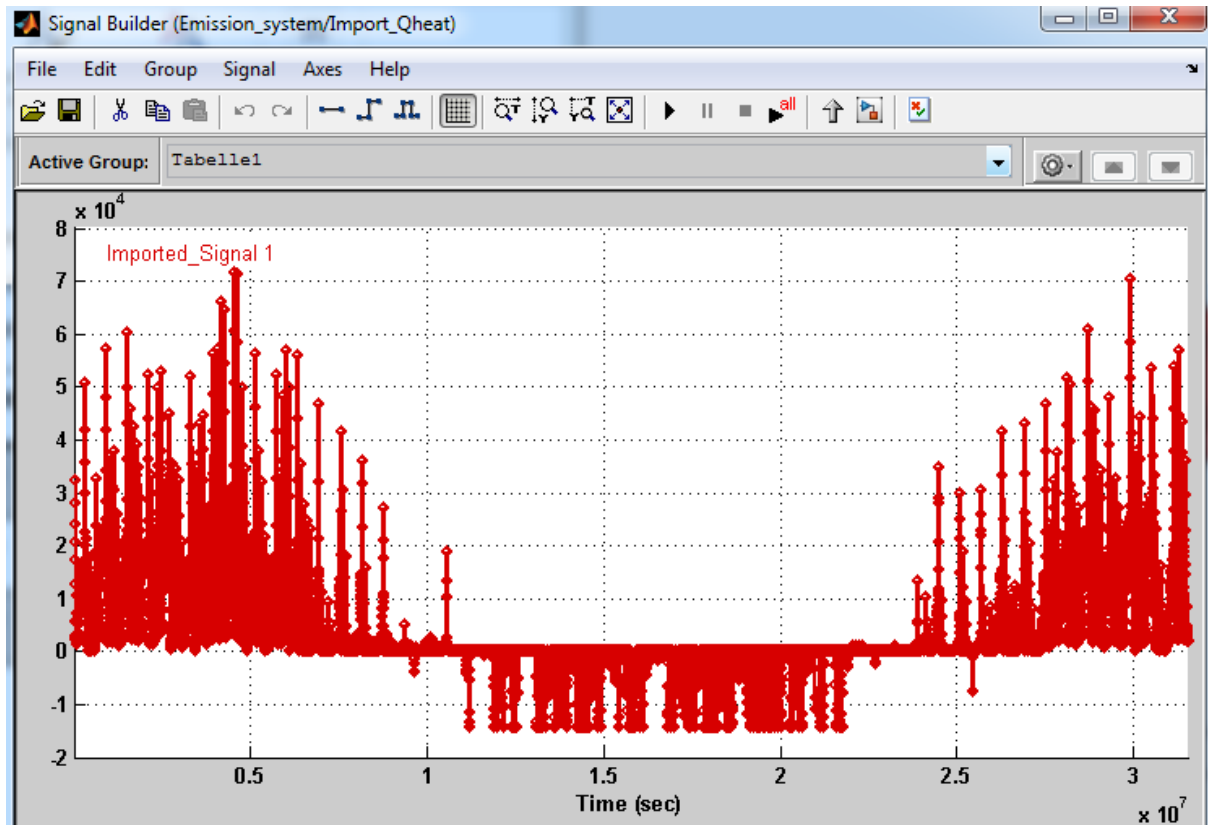


Figure 18: Power requirement passive house

3.3.2 DHW loads

The DHW loads were taken from measured values for office building with district heating (Ulseth, 2014). The load profiles are based on hourly measurements by a regular heat meter. The measurement shows a difference between workdays and weekends, this difference is taken into account in the simulation model as well. In Simulink a repeating sequence which represents one week is implemented and the values of this sequence are shown in the Figure 19 (blue).

To analyse the need of an exact load profile a simulation was performed with the average values for weekdays and weekend (red).

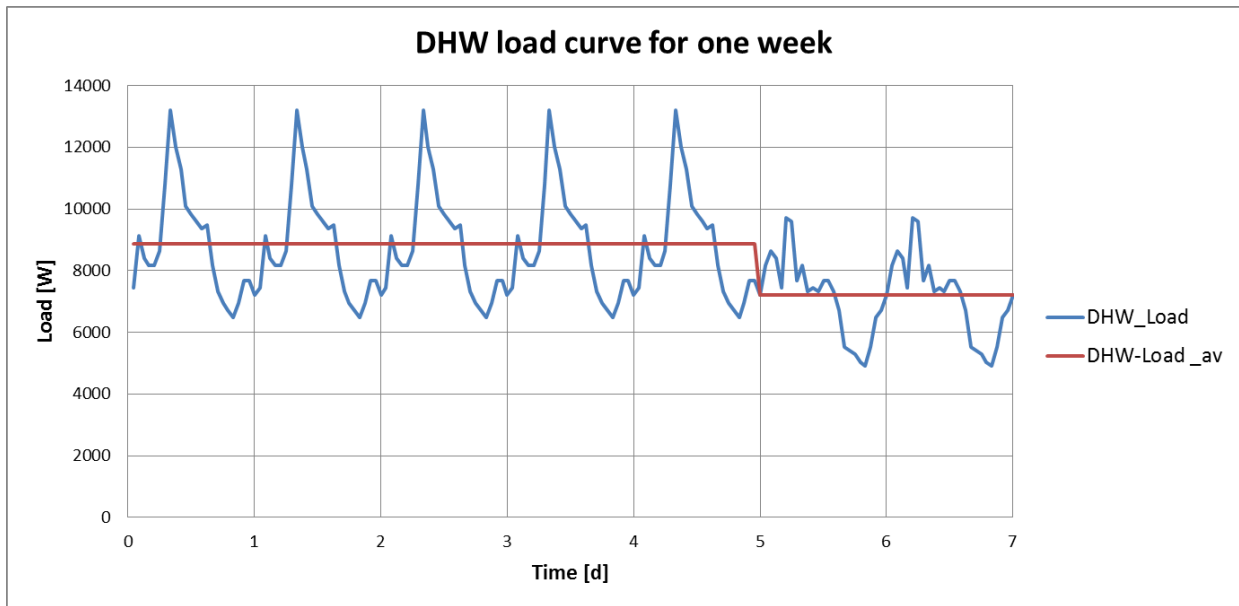


Figure 19: DHW load curve for one week

4 Results

The SimTool which is shown in this thesis was used to investigate different aspects of the BHS. All the results of the simulation including discussions and conclusions are listed in this section. The simulations were performed on Laurent Georges workstation, where it is possible to create 12 parallel workers which provides the opportunity to run two systems at the same time (each system consists of 6 simulations for the different HP-Sizes).

The output values are created with a time step of one hour; since the simulation itself is running on smaller time steps, the hourly output value is always the mean value over one hour. The ode23-solver, which is implemented in Matlab Simulink, was used to run the different simulations. This solver has the best performance and a high accuracy of the results. As already mentioned, the SimTool creates multiple output parameters which can be used to proof the performance of the SimTool itself as well as to analyse the influence different parameters on the whole building heating system. By using the cost and CO₂ emission implementation, a strong statement on the question about which system layout to use in a specific building, can be formulated.

The cost course over different coverage factors was generated by applying a third order polynomial regression on the cost value for the different HP-sizes.

To find an answer to all those questions, a large number of simulations was performed during the project. The naming shown below will help the reader to quickly understand which simulation results are presented.

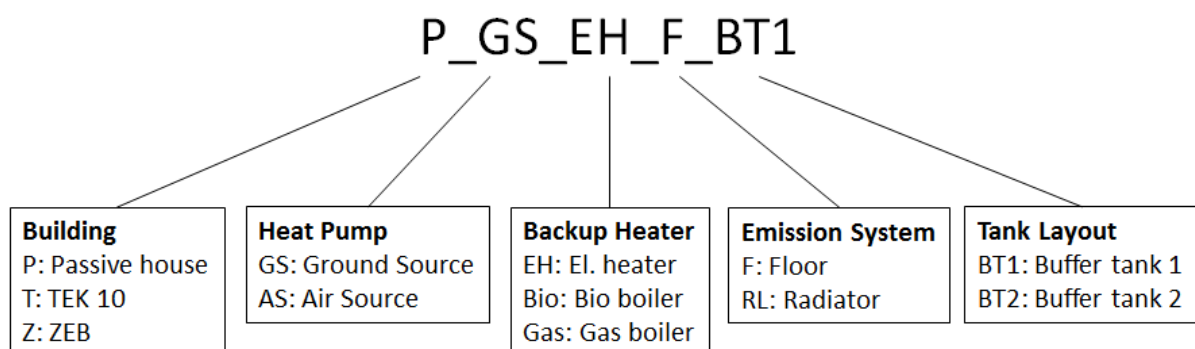


Figure 20: Naming results

4.1 Proof of Concept

In this chapter the performance of the simulation is proved using the P_GS_EH_F_BT1 model with a 40 kW HP. On this system different aspects like supply and tank temperatures as well as the delivered heating power are investigated and compared with the input.

4.1.1 Supply temperatures

The supply temperatures for the two systems are defined as input for both the DHW-, and the heating system. The mixer shown in section 0 is used to ensure that the supply temperature is equal to the set temperature.

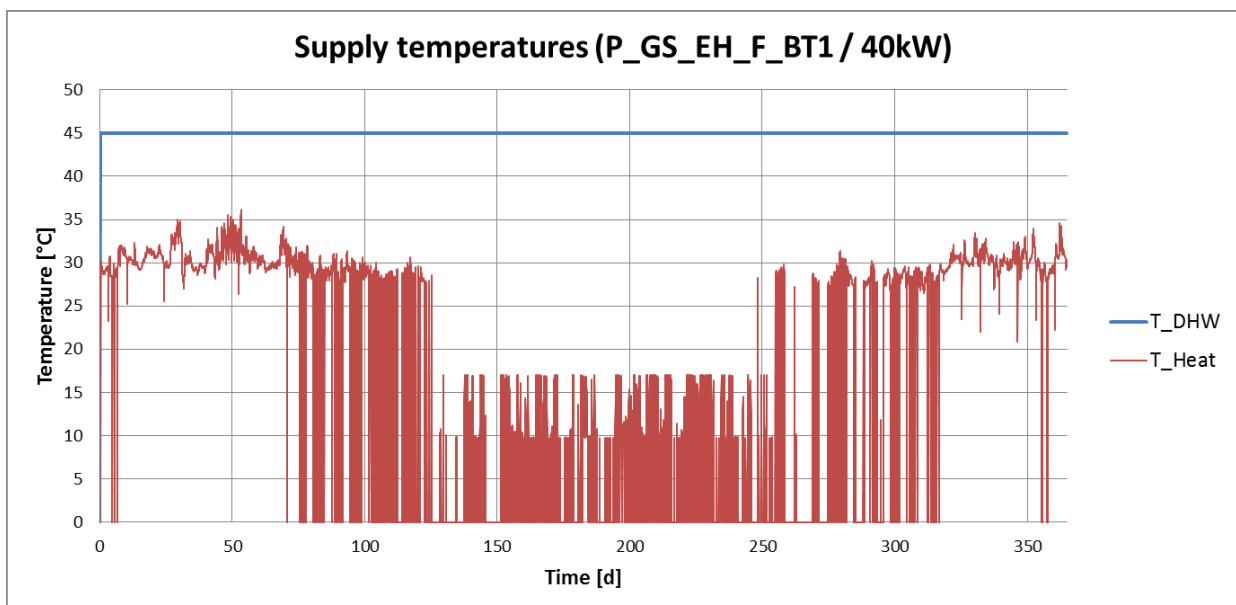


Figure 21: Supply temperatures (P_GS_EH_F_BT1 / 40 kW)

Discussion

Figure 21 shows the course of supply temperatures for the DHW-system (blue) and for the heating-system (red) over the period of one year. Notably, the supply temperature of the DHW-system is constant at 45°C during the whole year. The supply temperature of the heating-system varies from winter (around 30°C) to summer (around 16°C) and follows the set temperature which is calculated using the method shown in section 0 of this thesis. If the mass flow of the system is zero the temperature is displayed as zero as well, this is the reason for jumps in the heating temperature.

Conclusion

The system is at all times able to deliver the set heating and cooling temperatures as well as the set DHW temperature. This proves the function of the mixer as well as the performance of the control system on the tank temperatures. For further work, it might be interesting to analyse the influence of different temperature profiles.

4.1.2 Delivered power

In section 4.1.1, it was already shown that the set temperatures are properly followed by the supply temperature. During the simulation, the mass flow of the two systems is adapted to control the power delivered to the system.

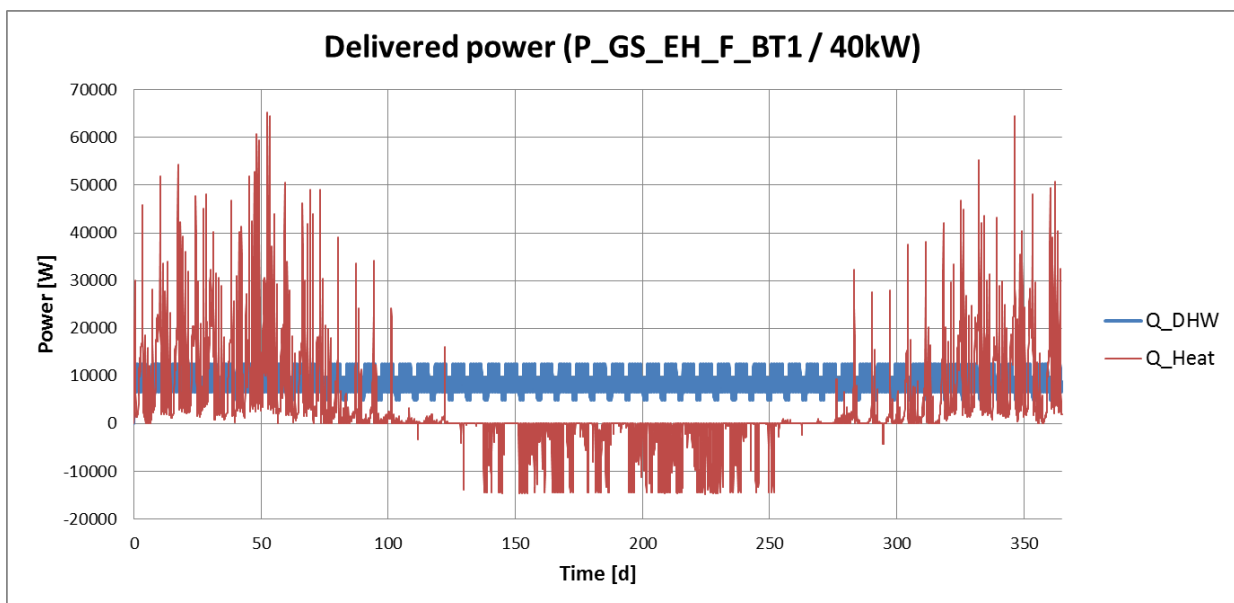


Figure 22: Delivered power (P_GS_EH_F_BT1 / 40 kW)

Discussion

In Figure 22 the course of the delivered power to the DHW-system (blue) and the heating-system (red) are shown. When these values are compared with the input loads shown in Figure 18 and Figure 19, it is apparent that they have the same size and the heating system is able to deliver the required power during the whole year. In appendix 4 the comparison of those two curves is shown for one week during winter and one week during summer. There is no difference recognizable in both plots.

Conclusion

The power control by varying the mass flow which is implemented in the SimTool works fine and the DHW-system as well as the heating-system are depicted correctly.

4.1.3 Tank performance

The temperature control of the two buffer tanks shown in section 3.2.2.3 of this thesis is investigated and discussed here.

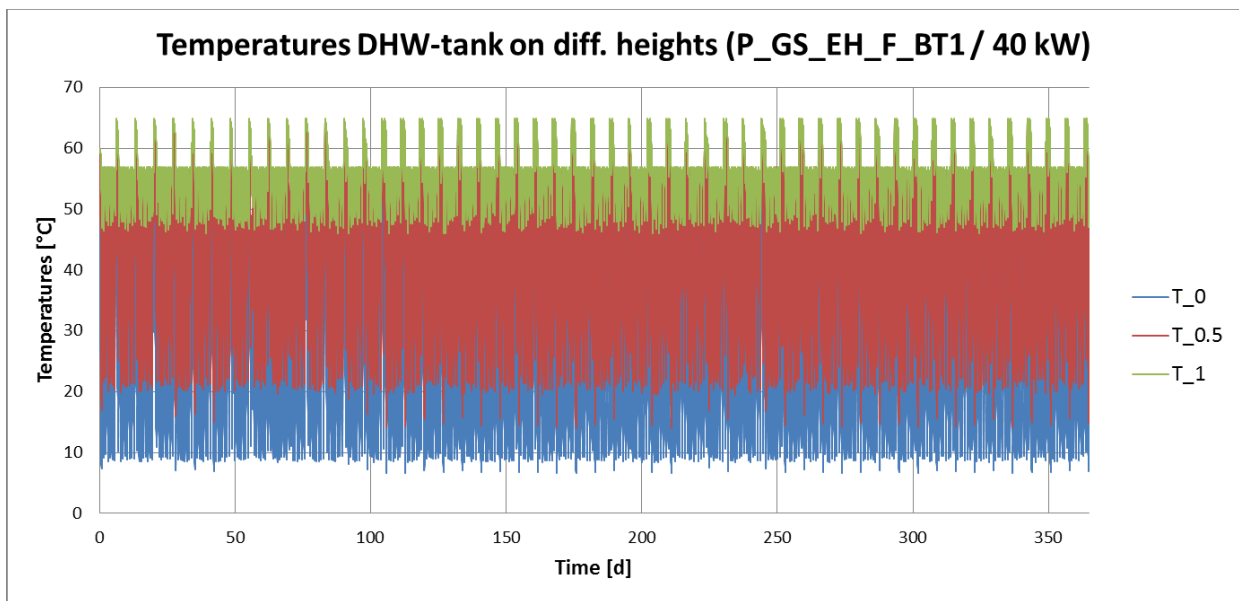


Figure 23: Temperatures DHW-tank on different heights (P_GS_EH_F_BT1 / 40 kW)

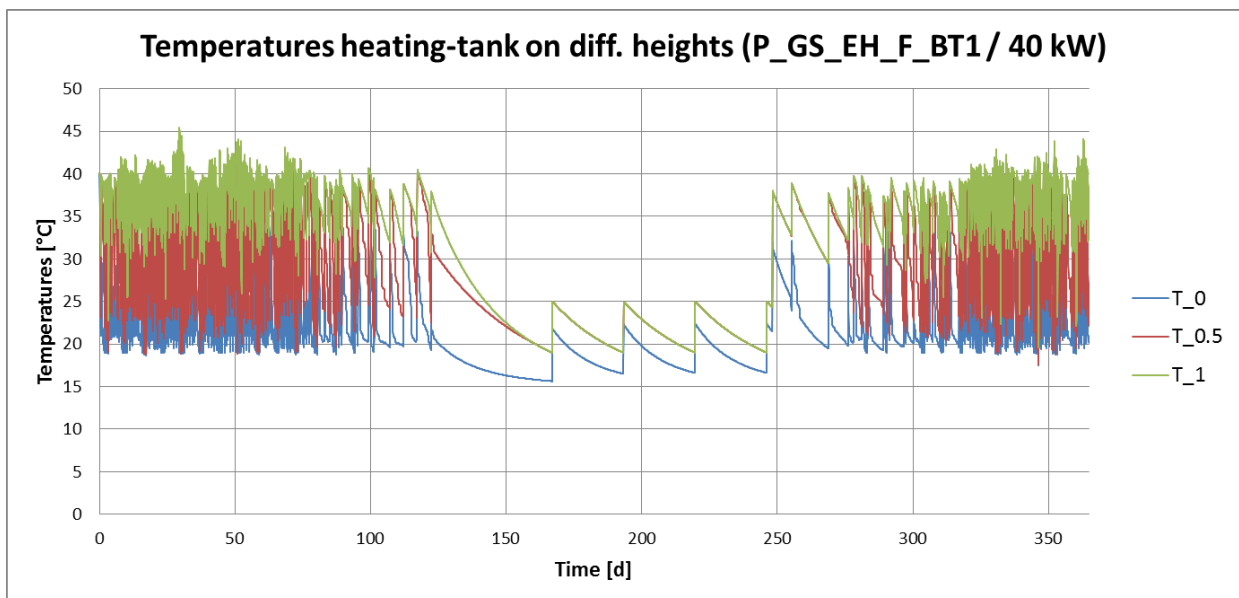


Figure 24: Temperatures heating-tank on different heights (P_GS_EH_F_BT1 / 40 kW)

Discussion

Temperatures: The annual courses for the temperatures in the two buffer tanks are shown in Figure 23 and in Figure 24. These figures contain the temperature data at three different nodes (bottom = blue, middle = red, top = green). The temperatures in the heating-tank are constant over the year with weakly increases due to the week setback. It is also to see, that the temperature at the top is never below 45 °C; this is important for the system to be able to deliver the required temperature to the DHW-system. The analysis of the week setback is shown in the Figure 25 where the temperature course over two weeks is depicted. One can see that the tank temperatures in the whole tank increase over 60°C once a week. The temperature of the heating-tank is set to be always 5 °C higher than the supply temperature during the heating period and constant on 20 °C during the cooling period. These settings can be seen in the Figure 24 and it is also important to note that the tank needs to be reheated during the cooling period although there is no load on the tank. This is due heat losses of the tank which occur because there is a constant ambient temperature of 15 °C set for the simulation.

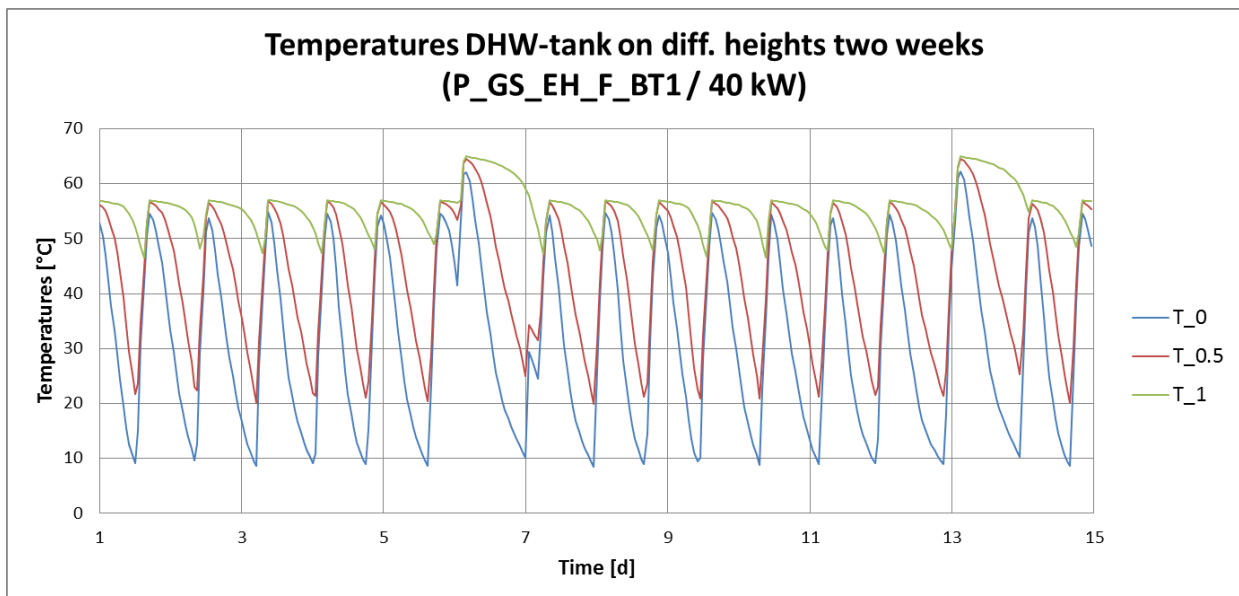


Figure 25: Temperatures DHW-tank on different heights two weeks (P_GS_EH_F_BT1 / 40 kW)

Thermal energy losses: In Figure 26 and Figure 27 the thermal energy losses are summed up over one year. Figure 26 shows a curve with a constant slope, which states that the thermal losses on the tank are constant during the whole year. Furthermore HP 1 led to the highest energy losses; this is due to the highest annual average temperature for this HP. The slope of the energy losses curve for the DHW-tank shown in Figure 27 shows

that the thermal losses are smaller during the summer due to the lower tank temperatures. Here the losses of the HP 1 are smaller and this can be explained by the tank temperatures as well. In a system with small HP's, the DHW-tank is mostly heated by the BUH. Since the BUH is just heating the top part of the tank, the lower part stays at low temperatures and thereby produces like smaller losses.

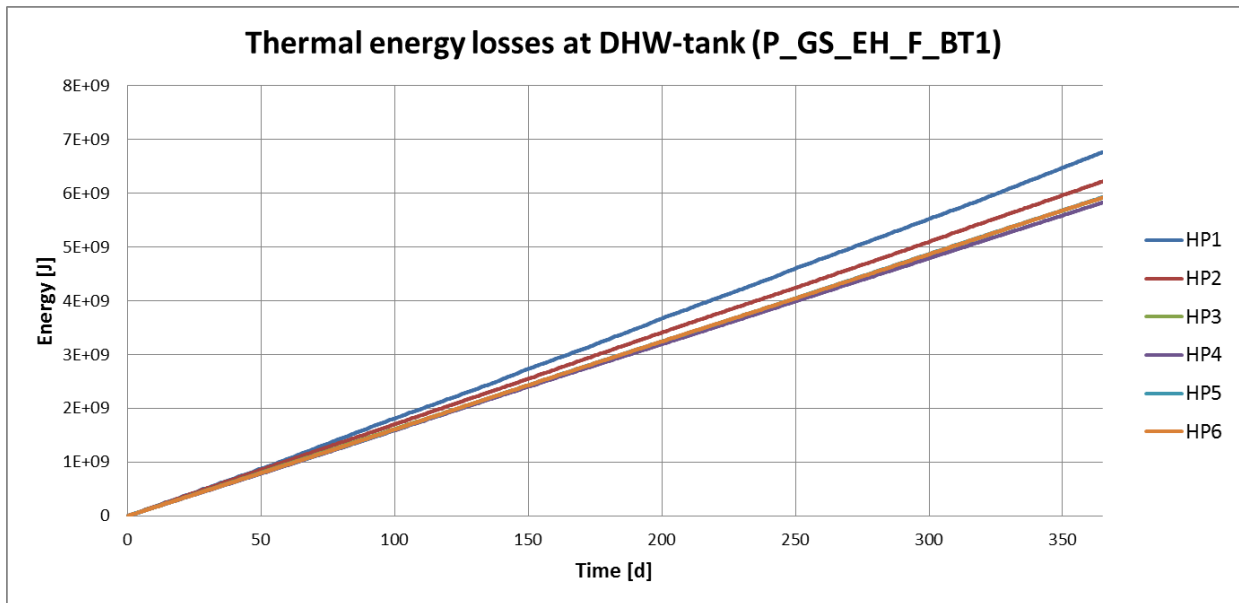


Figure 26: Thermal energy losses at DHW-tank (P_GS_EH_F_BT1)

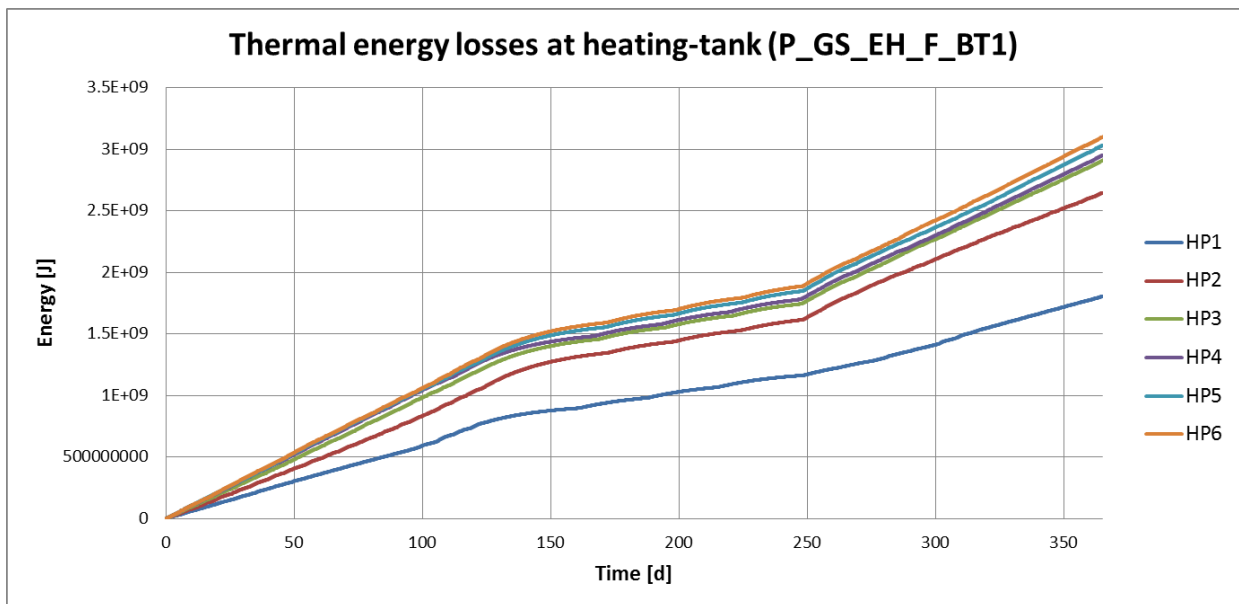


Figure 27: Thermal energy losses at heating-tank (P_GS_EH_BT1)

Conclusion

The two tanks and its control are working properly, so the required temperature levels are always available. The mechanism to prevent the formation of legionella's is proven since the whole tank is heated over 60°C once a week. One thing that can be improved is the summer performance of the heating-tank. In normal systems, there is now power supply on the heating-tank during the summer. This can be implemented in this model by changing the summer set temperature to a value lower than the annual ambient temperature (in this case 15 °C). For these cases, the course of the thermal losses shown in Figure 27 should be horizontal during the summer period.

4.1.4 Heat pump performance

The model of the HP and the different performance curves used for this simulation are show in section 3.2.1 of this thesis. In this section the HP-performance is investigated using a 6 kW HP in the P_GS_EH_F_BT1 model. The 6 kW HP is used because it is running during the whole year on the DHW-Tank and this keeps the temperature level on the hot side constant.

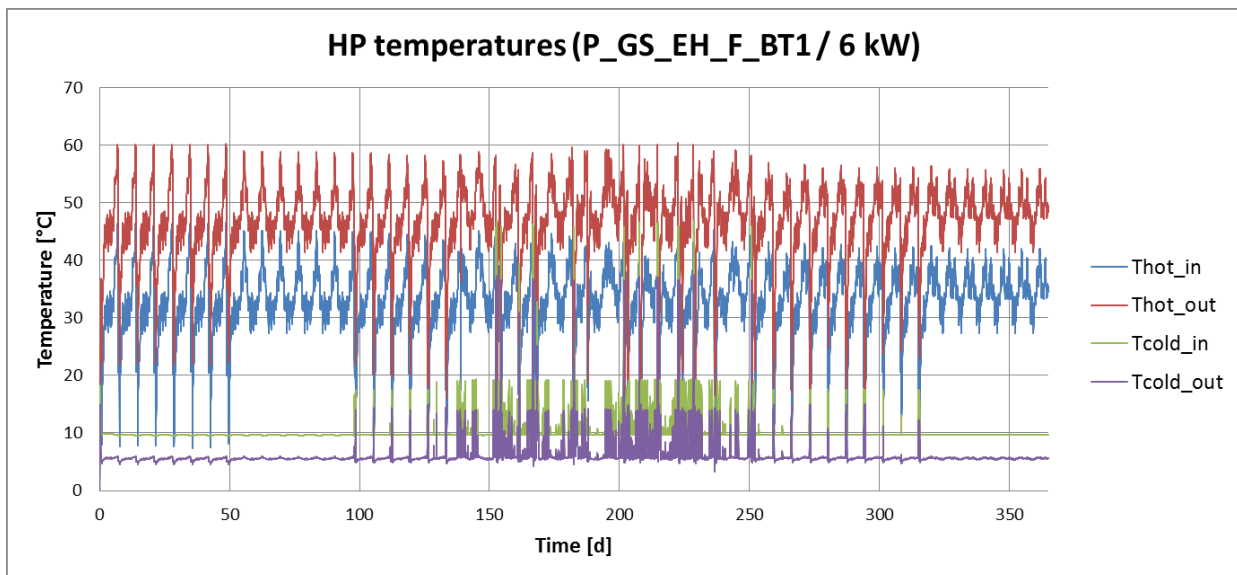


Figure 28: HP temperatures (P_GS_EH_F_BT1 / 6 kW)

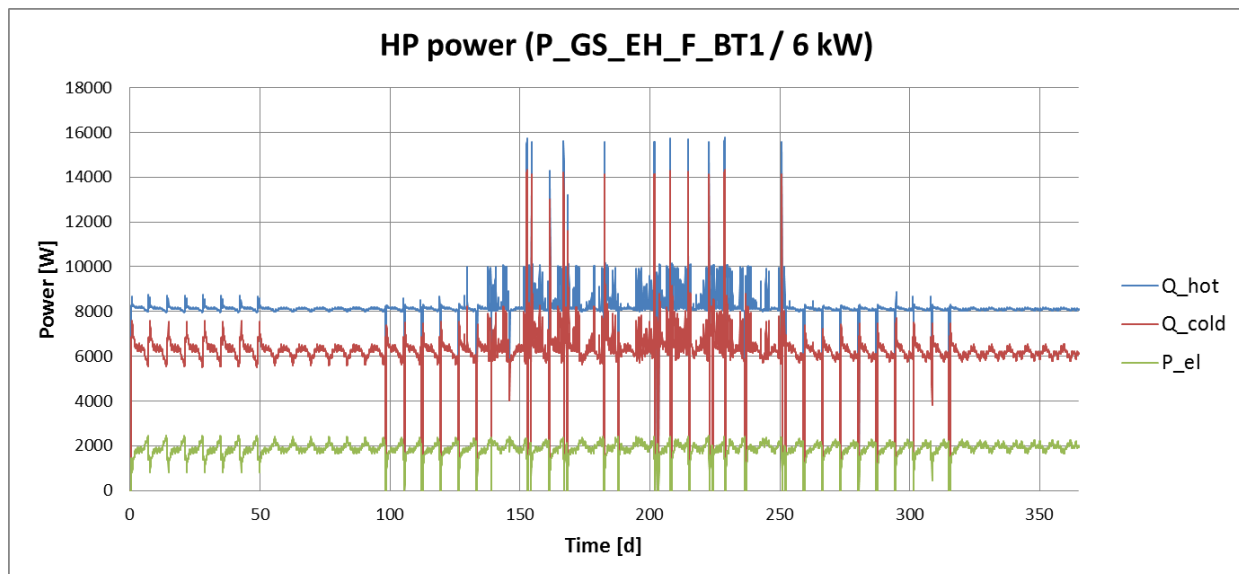


Figure 29: HP power ($P_{GS_EH_EH_F_BT1} / 6 \text{ kW}$)

Discussion

The annual course of the temperatures (Figure 28) and the power (Figure 29) shows the difference between summer and winter performance of the HP. During the winter, the ground source is able to deliver a constant temperature of 10 °C thanks to the free cooling the temperature increases during the summer. This influence can be seen in the figures in appendix 4, where the temperature course for one week during summer and one week during winter are shown.

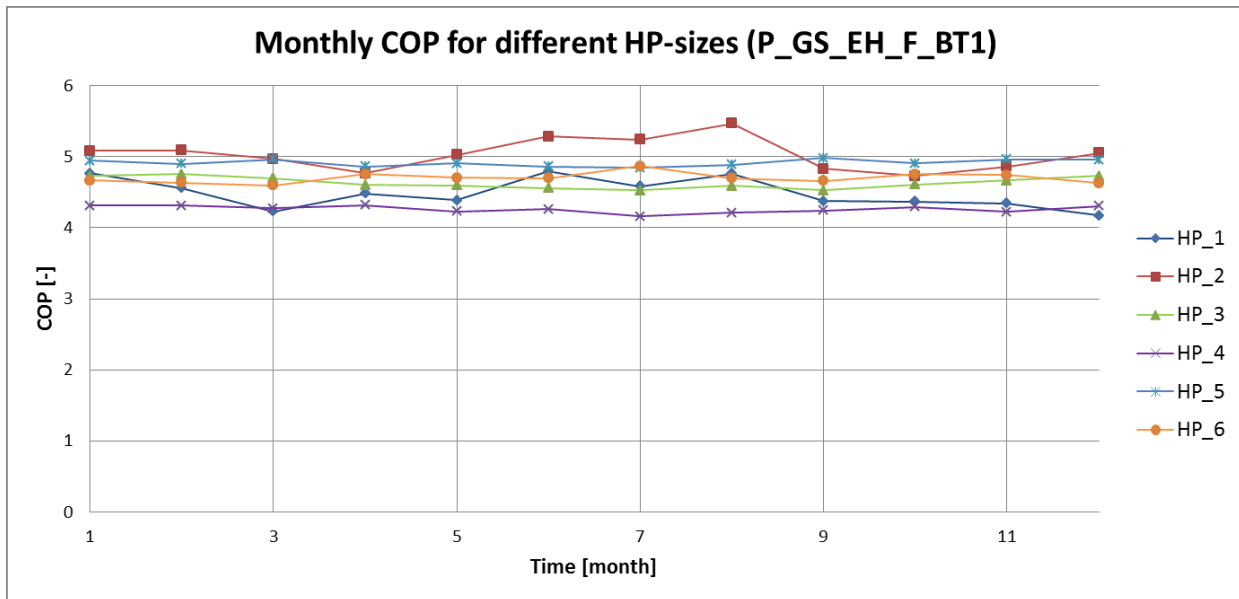


Figure 30: Monthly COP for different HP-sizes (P_GS_EH_F_BT1)

In Figure 30 the values of the monthly average of the coefficient of performance (COP) are listed. Due to the free cooling the source temperature during the summer is higher and higher COP's are expected. This fact can be seen for the small HP's; for the bigger HP's where the COP is approximately constant over the whole year. The reason for this statistic is that big HP's work on both on the DHW-tank and on the heating tank during the winter whereas the small HP's work just on the DHW-tank (see Section 4.1.5). If we look at the temperatures levels for those tanks it can be seen that the temperatures in the heating-tank are lower than the temperatures in the DHW-Tank and this causes that the HP to work on a higher COP while supplying the heating-tank. Some weekly courses which show that fact are included in appendix 4.

Conclusion

The comparison of the loads with the performance curve of the HP shows that the results are in line and the implementation of the HP is done properly. One can also see the influence that they system has on the HP is visible as well and this provides the opportunity for an exact HP-review for different combinations.

4.1.5 Delivered energy

The system has two components which are delivering energy in terms of heat to the system. In this section the amount of produced energy per system is investigated using the P_GS_EH_F_BT1 system.

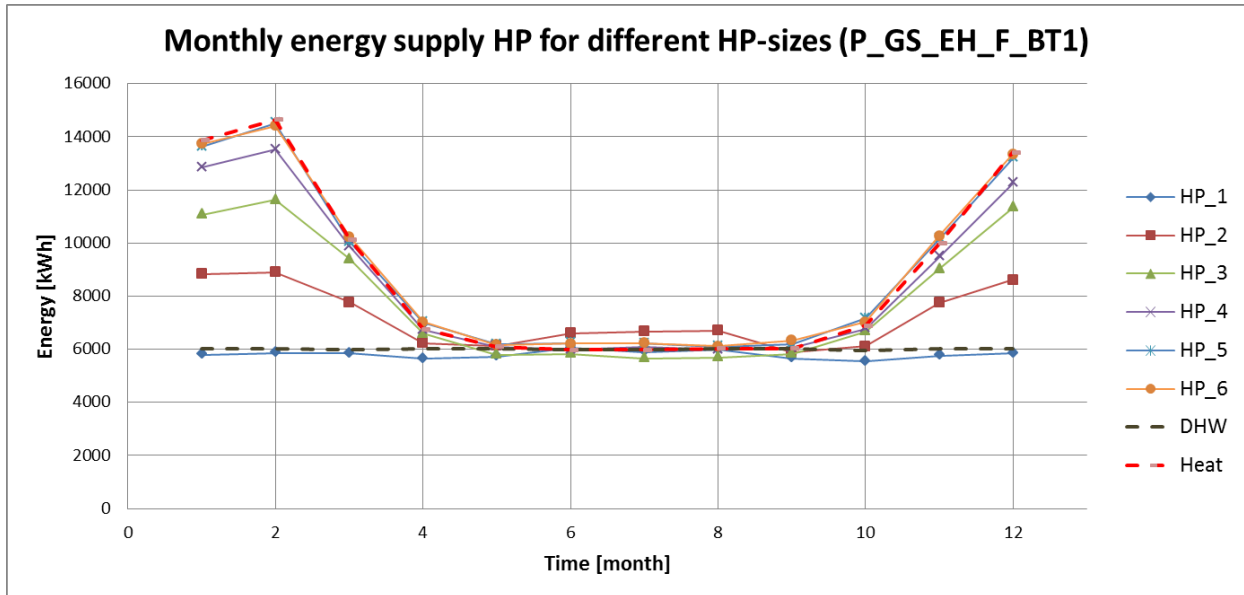


Figure 31: Monthly energy supply HP for different HP-sizes (P_GS_EH_F_BT1)

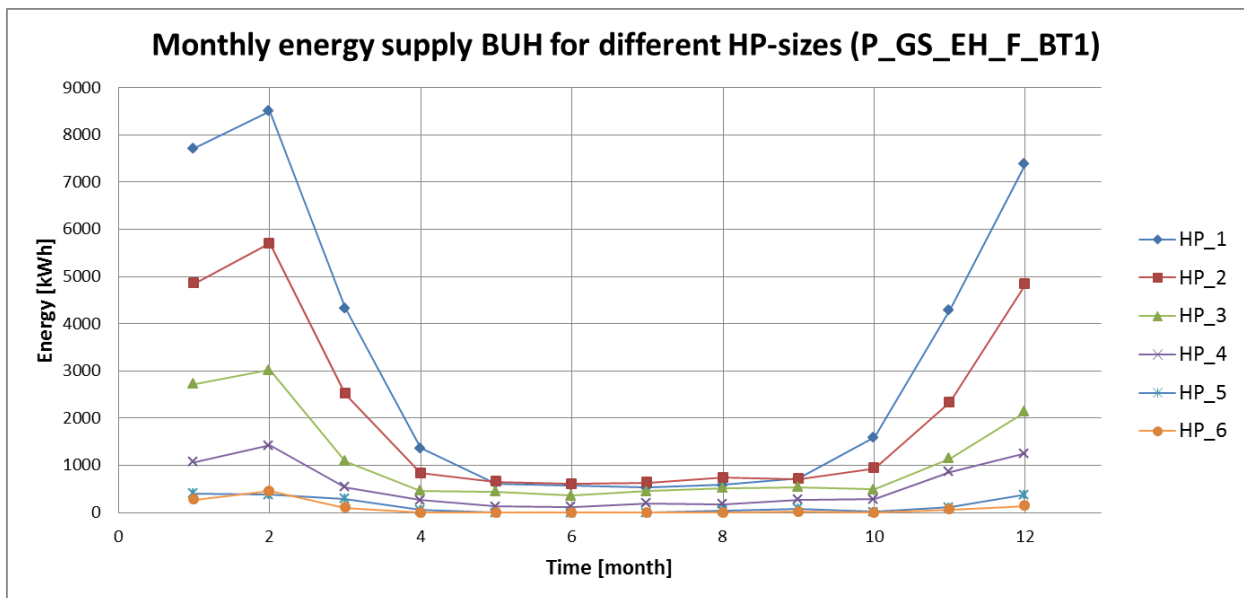


Figure 32: Monthly energy supply BUH for different HP-sizes (P_GS_EH_F_BT1)

Discussion

Figure 31 shows the monthly energy supply for the different HP-sizes as well as the loads for DHW and heating (dotted lines). Figure 32 shows the monthly energy supply by the BUH for the different HP-sizes. If we compare the loads to the supply power shown in Figure 31, it is apparent that the 6 kW HP is just able to cover the DHW-loads by running the whole time. On the other hand, the 75 kW HP is able to cover both DHW- and heating-loads. This leads to the result shown in Figure 32, where the BUH for small HP's need to work a lot during winter but the BUH for big HP's see minimal use during the whole year. Another way to display this fact is the use of duration curves as shown in Figure 33. The runtime as well as the delivered power can be seen there for different HP-sizes. The dotted lines mark the difference between HP and BUH, and it is to see that for small HP's the area over the line is bigger, which is explained by higher energy supply by BUH. This difference between BUH and HP is shown clearly in the duration curves shown in the appendix 3.

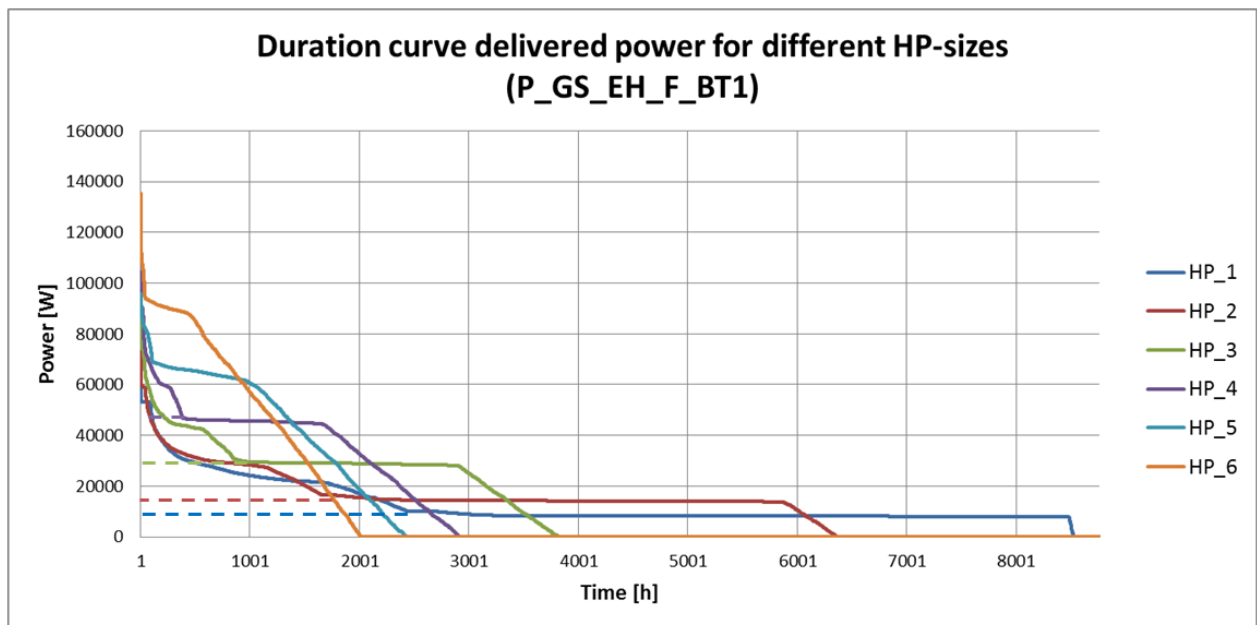


Figure 33: Duration curve delivered power for different HP-sizes

The monthly average seasonal performance factor (SPF) shows the influence of the energy supply system (HP or BUH) on the performance of the whole system. For the 75 kW HP the SPF is roughly constant over the year and just slightly lower than the COP of the HP (see Figure 30). The fact that the electric BUH implemented in this system has an

efficiency of 0.9 lowers the SPF when the BUH is running a lot; this can be seen during the winter for the small HP's.

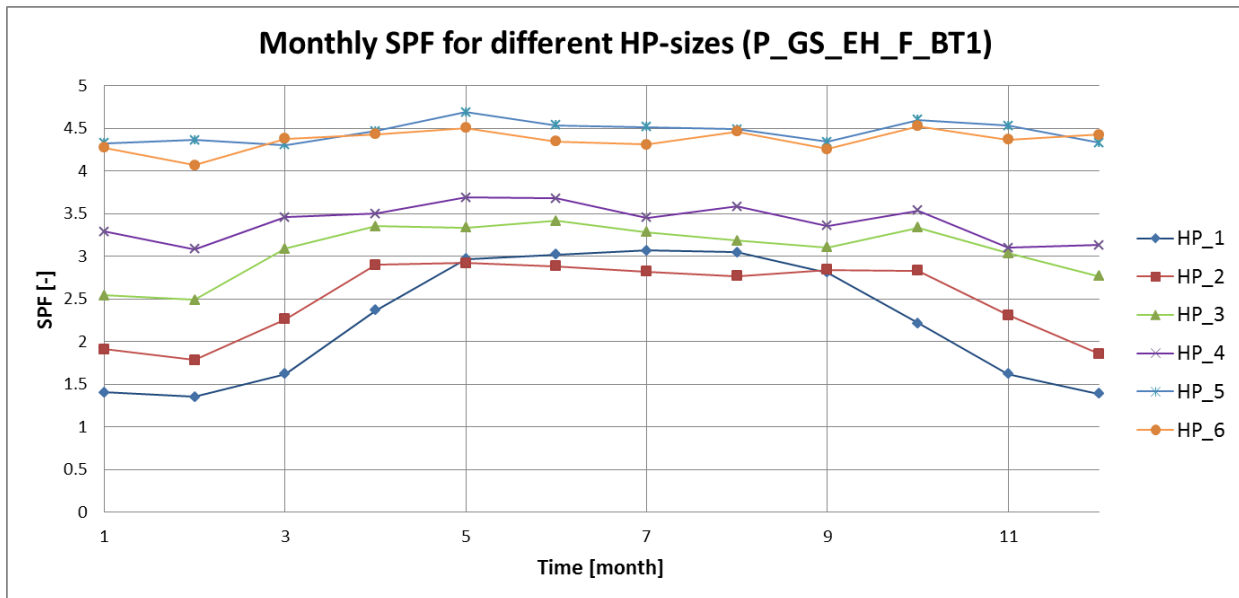


Figure 34: Monthly SPF for different HP-sizes (P_GS_EH_F_BT1)

Conclusion

The SimTool allows for deep investigation of the delivered energy, the runtime of the components and the performance of the system as a whole. This can be used to study different system combinations, load profiles and control systems. One thing that can be examined is for example an intelligent loading of the tanks where the heating tank is loaded when the HP is available and not just when the temperature is too low. This way the simultaneous running of HP and BUH can be prevented and the BUH shouldn't be used at all for the big HP's. Also tank loading using a given profile which is running the HP at times when there is low energy consumption in the grid (e.g. night) as well as the influence of curfew's for the HP during the day are interesting points to investigate.

4.2 Comparison previous thesis

In the section 4.1 the function and the performance of the SimTool is proven, this chapter now focuses on comparing the results of the previous thesis to my results generated with the SimTool. The comparison is based on the course of the costs over the different

coverage factors of the HP. The model used for this comparison is the Z_P_GS_EH_BT1 since there are results available for this model in the previous thesis (Figure 36).

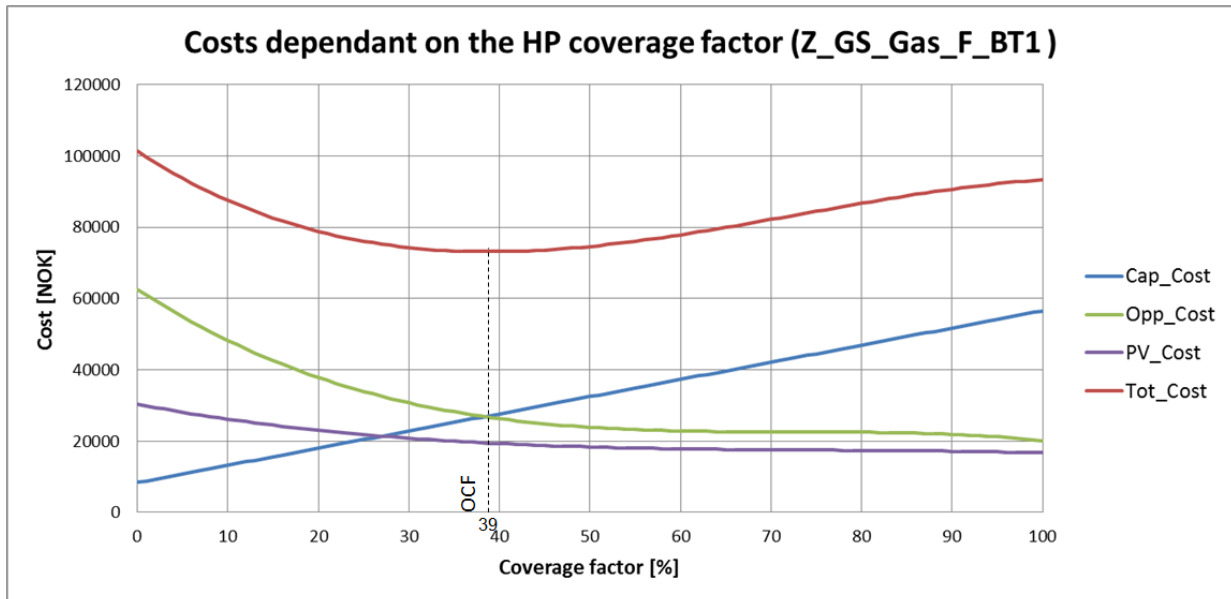


Figure 35: Cost dependant on HP coverage factor (Z_GS_Gas_F_BT1)

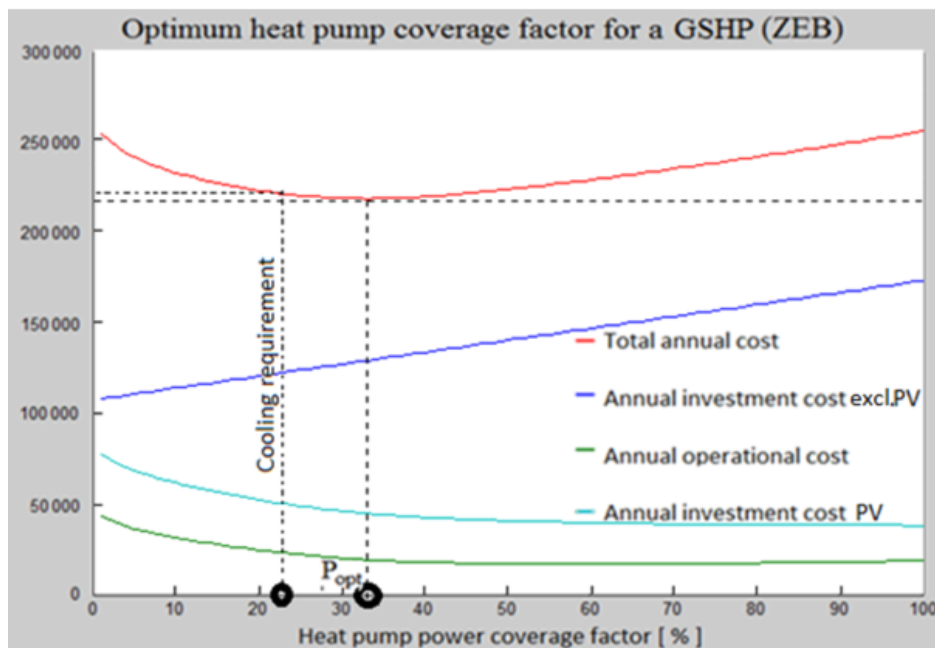


Figure 36: Cost comparison (Småland, 2013)

Discussion

The cost curves shown in Figure 35 and Figure 36 are more or less similar in the shape and the values; nevertheless there are some differences which are discussed below.

Optimal coverage factor (OCF): The OCF resulting of the simulation with the previous tool (35 %) is slightly lower than the one received with the SimTool (39 %). This change can be explained by the more accurate investigation of the electric consumption in the whole system. The previous tool just includes some rough assumptions to calculate the electric power used in the system. In contrast, the SimTool takes into account the exact consumption of all the different components. This fact can be seen in the operational costs where the slope decreases faster for the SimTool.

Investment Costs: The annual investment costs using the SimTool are around 100'000 NOK lower than the one from the previous tool. The reason for this is that the previous tool takes into account investment costs for the whole heating system, where the new simulations tool just calculates the costs for the components implemented in the Simulink model. Nevertheless, the difference of the investment costs between a 0 % and a 100 % coverage factor is the same for both simulations. That means that the OCF is not influenced by this difference, the costs are just a constant offset lower.

Cost PV: The investment costs for the two different simulations are decreasing at higher coverage factors for both simulations, but they are smaller for the SimTool. This change cannot be explained by comparing the two simulation models. It can be that there is an uncertainty in the cost calculation of the PV-System. Since it only has an influence on the costs for the ZEB-building it was not examined more closely during this project but should be investigated in a next step.

Conclusion

The investigations in this section show that the two simulation tools create similar results. Since there are a lot of different parameters in the whole Simulink model, it is possible that one of those parameters affects the result and therefore it is recommended to do further research into the parameters implemented in the Simulink model. In addition, both models fulfil the rules of thumb for building heating systems in Norway shown in section 2.1..

4.3 Impact parameters

In this section the impact of different input parameters or different components is investigated. The influence of the changes is always compared to the base model P_GS_EH_F_BT1.

4.3.1 Impact building

As described in section 0, there are three different building types implemented in this SimTool. The building loads used in this simulation were generated in another program (SIMIEN) and then imported to the Simulink model.

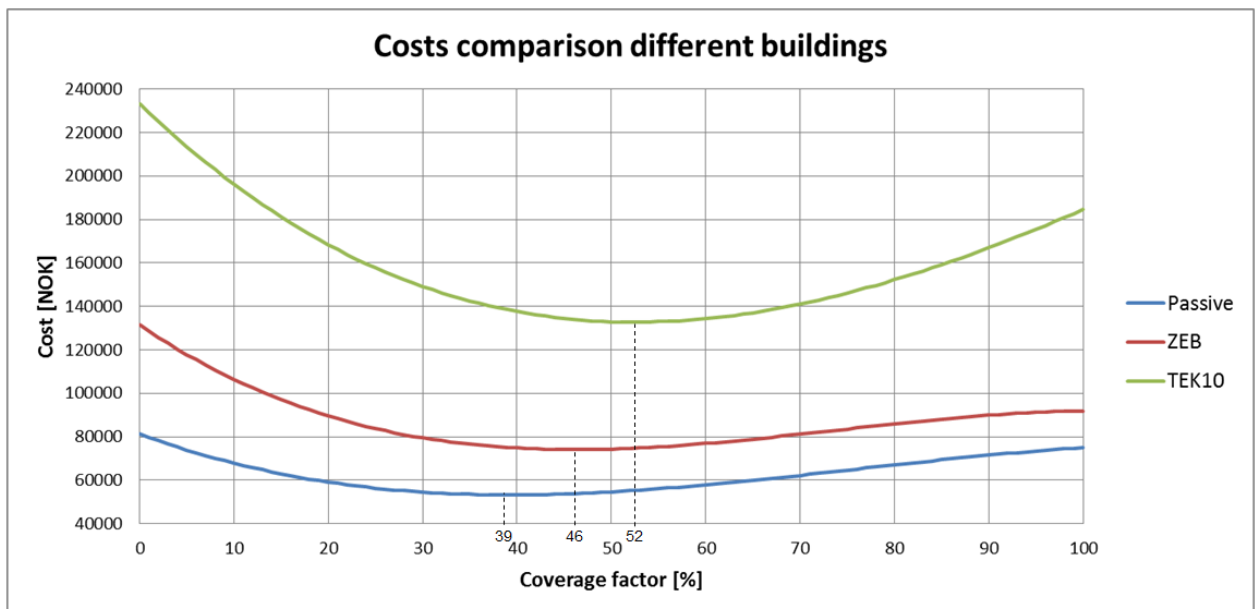


Figure 37: Cost comparison different buildings

Discussion

Figure 37 shows that the building has a large influence on the total cost as well as the OCF. The additional costs for the ZEB building compared to the passive building are the investment and maintenance costs of the PV-panels. For a lower coverage factor, the system consumes more energy and this leads to higher PV-costs at low coverage factors. This fact is also the reason why the OCF increases for ZEB compared to the passive building. Since the energy need for the TEK 10 building is higher, the operational as well as the investment costs higher. The fact that the OCF is increasing shows that the

operational costs raise faster compared to the investment costs. Figure 38, where the duration curve of the power supply for a passive building and a TEK 10 building at OCF are shown, demonstrates the higher power demand of a TEK 10 building.

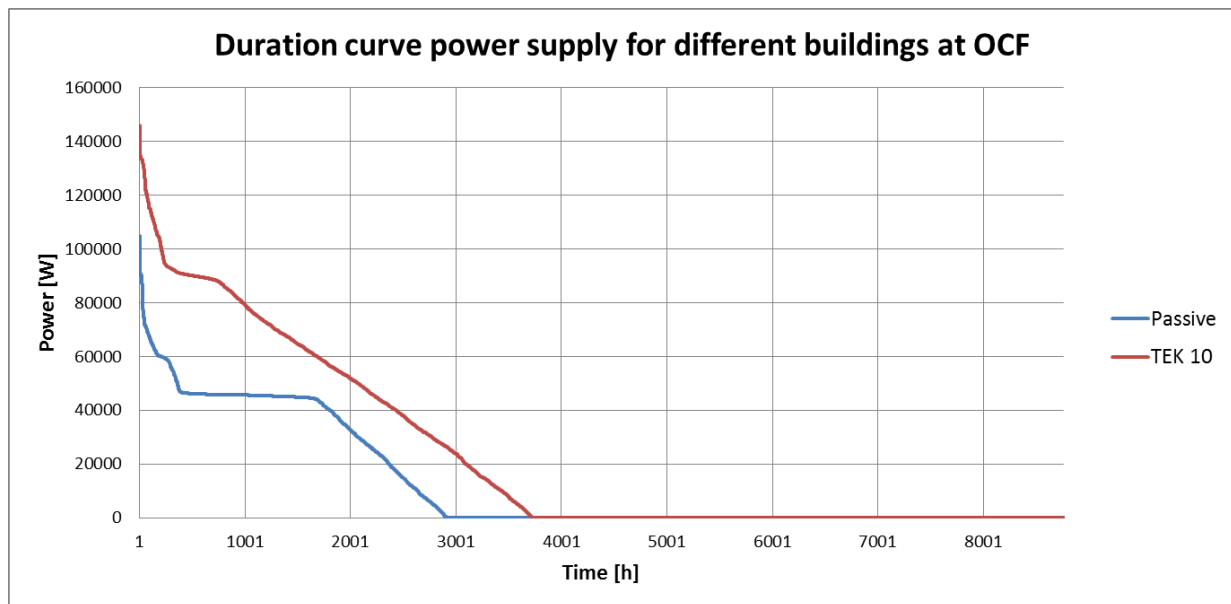


Figure 38: Duration curve energy supply for different building at OCF

Conclusion

The results of this investigation show that a clear definition of the building is needed first before focusing on the building heating system. The installation of PV raises the costs but nevertheless is an important opportunity to lower the CO₂ emissions produced in building sector.

4.3.2 Impact BUH

As already mentioned three different BUH-systems are implemented in the SimTool. This allows for a comparison and discussion on the influence of the different systems which is done in this section by comparing them to the P_GS_EH_F_BT1 model.

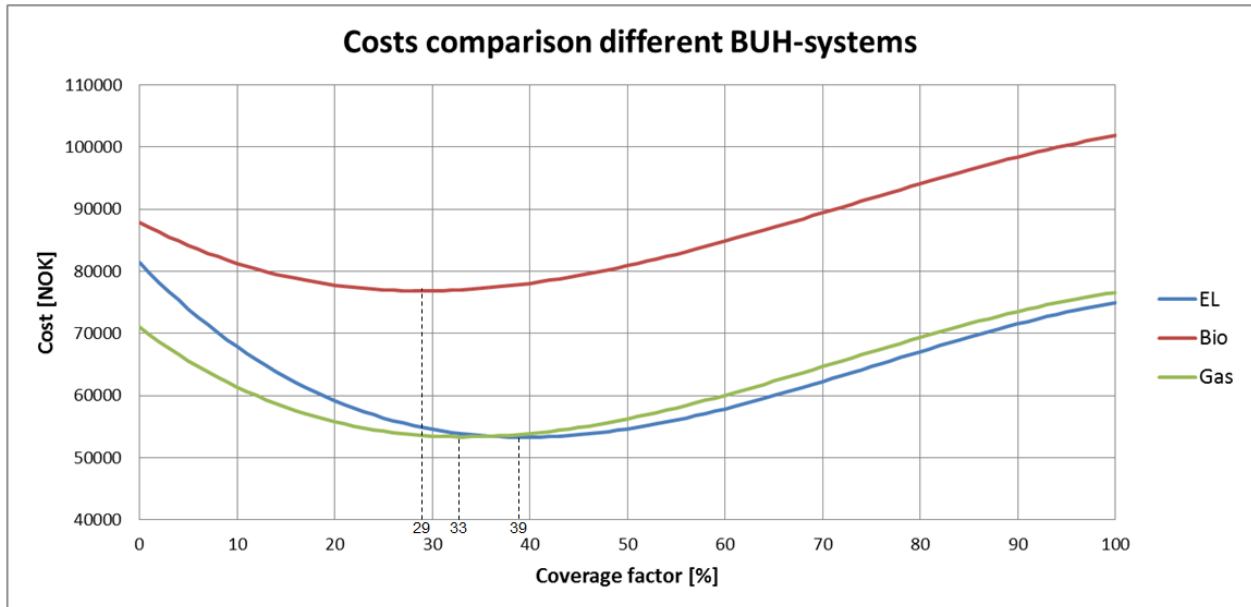


Figure 39: Comparison different BUH-systems

Discussion

The comparison of the total cost for the different BUH is shown in Figure 39. It shows that the rule of thumb, which says that a cheap BUH system is favourable, is fulfilled. The costs for the Bio heater (8000 NOK/kW) are way higher than for the electric heater (500 NOK/kW) or for the Gas heater (1000 NOK/kW). In Figure 39 it can be seen that the OCF's are vary for the different BUH-systems. These variations in the coverage factor are due to the different investment, maintenance and energy costs as well as the different power supply which is shown in the Figure 40 for the 6 kW HP. It is shown there, that the Bio- and Gas-boiler deliver more energy to the system than the electric heater. On the other hand, the HP connected with the electric heater run longer and delivers more power to the system and reducing the OCF values this way.

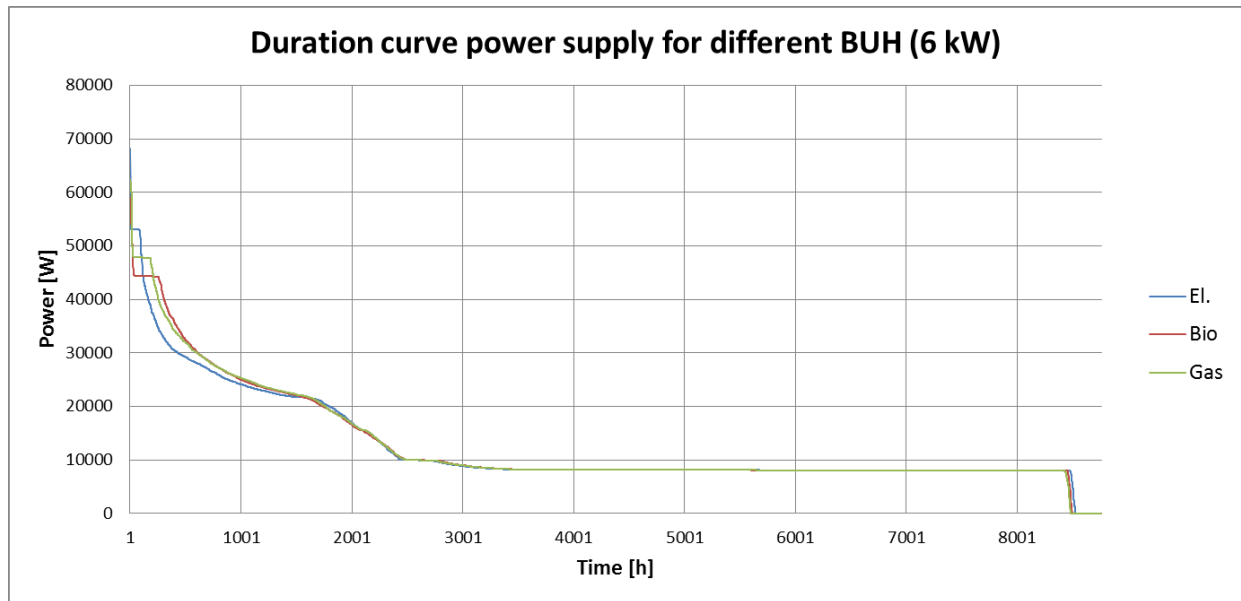


Figure 40: Duration curve power supply for different BUH (6 kW)

Conclusion

These investigations show that the differences between the BUH-systems are mostly because of the different prices of the systems. That is why it is important to have a clear idea about the prices for each system. Nevertheless this simulation tool provides the user with a lot of possibilities to investigate other factors linked to the BUH. For example, the size of the BUH can be changed according to the size of the HP, resulting in possible combinations of a big HP coupled with a small BUH or a small HP coupled with a big BUH.

4.3.3 Impact tank layout

The simulation tool has two different tank layouts implemented which are shown in section 3.2.2 of this report. The investigation of the performance and the costs of those two layouts are shown in this section.

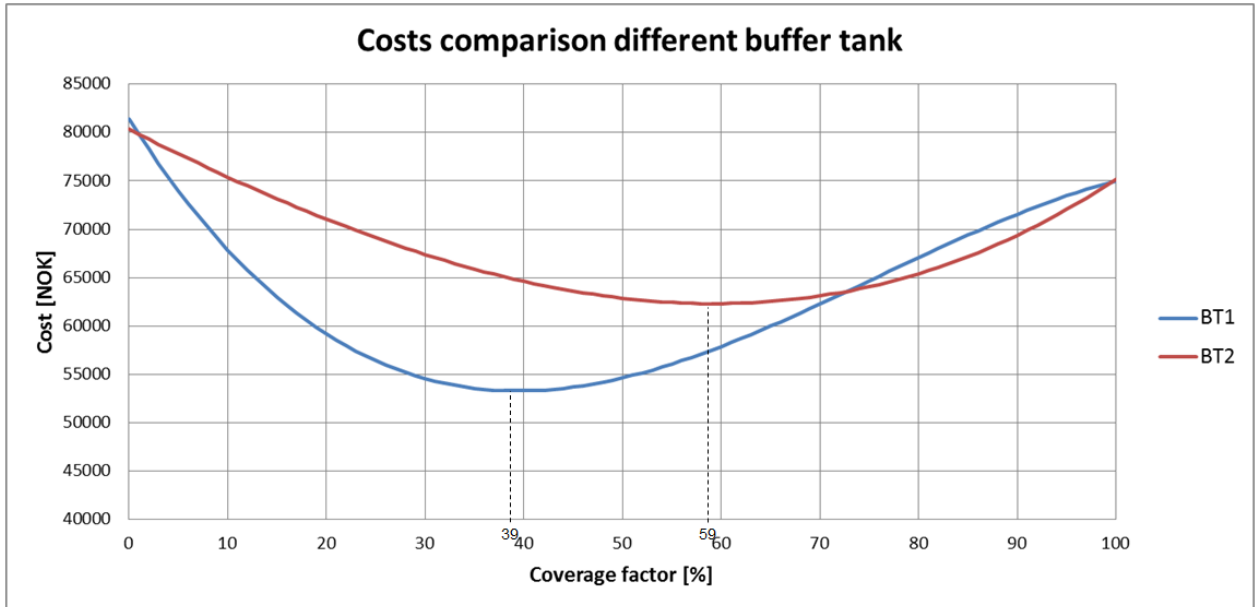


Figure 41: Cost comparison for different tank layouts

Discussion

Figure 41 shows the influence of the tank layout on the total cost as well as the optimal coverage factor, which are both varying a lot for the two tank layouts. The optimal coverage factor rises from 40 % for BT1 up 60% for BT2. The duration curves of the power supply showed in Figure 42 illustrate the reason for this. The system with BT2 consumes more “expensive” energy from the BUH while the BT1 system covers this requirement with “cheap” energy from the HP.

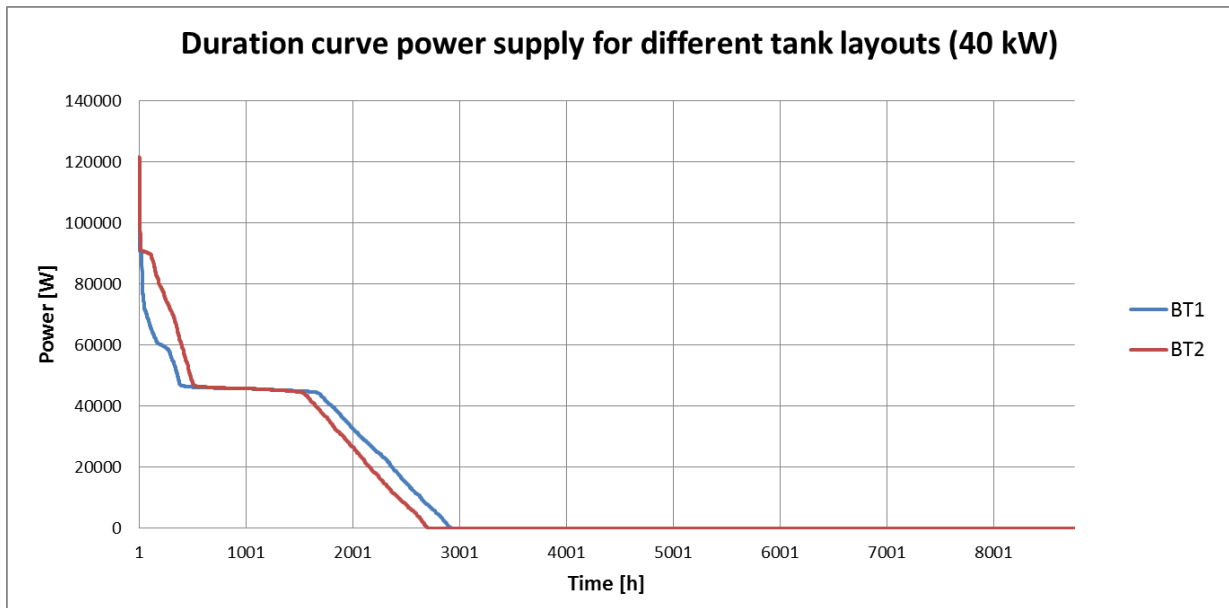


Figure 42: Annual electric power consumption for different tank layouts

The reason for the higher energy consumption in the BUH is shown in Figure 43 and Figure 44, where the courses of the temperatures at different nodes in the tank are illustrated. Since the height of the input is changing for the two layouts as shown in Figure 10 and Figure 11, the BUH connected to BT2 always heats up the whole tank where the BUH connected to BT1 is just working on the top and heats the tank just until the 0.7 node where it is connected. In other words, the BUH in BT2 heats up the whole tank where the BUH in BT1 just heats the top.

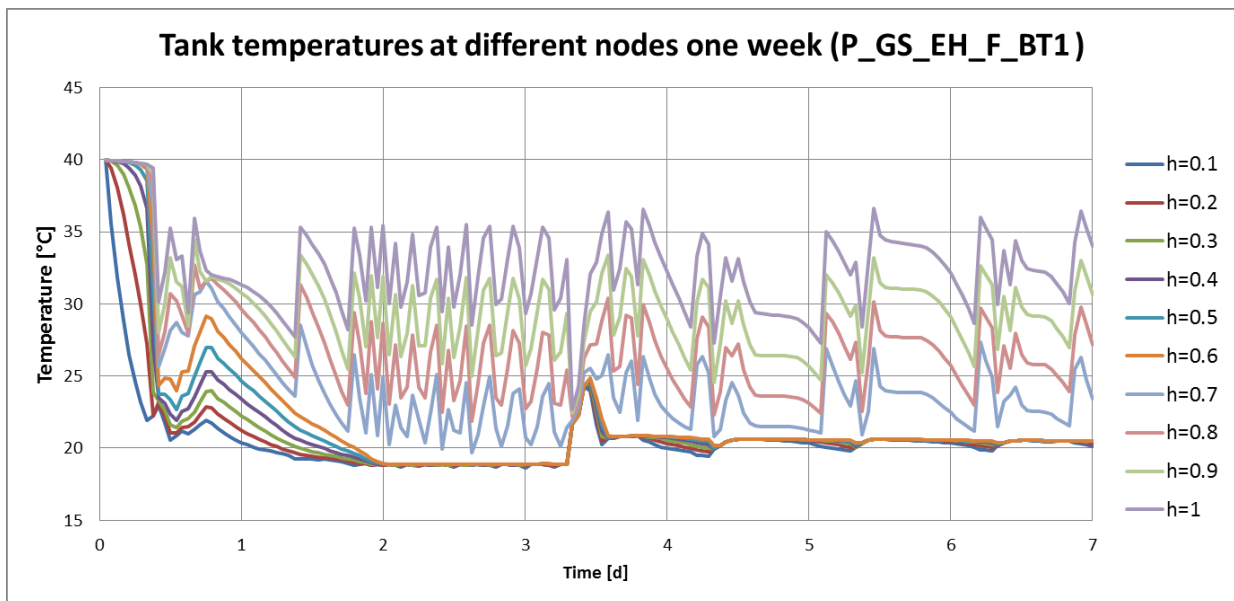


Figure 43: Tank temperatures at different nodes one week (P_GS_EH_F_BT1)

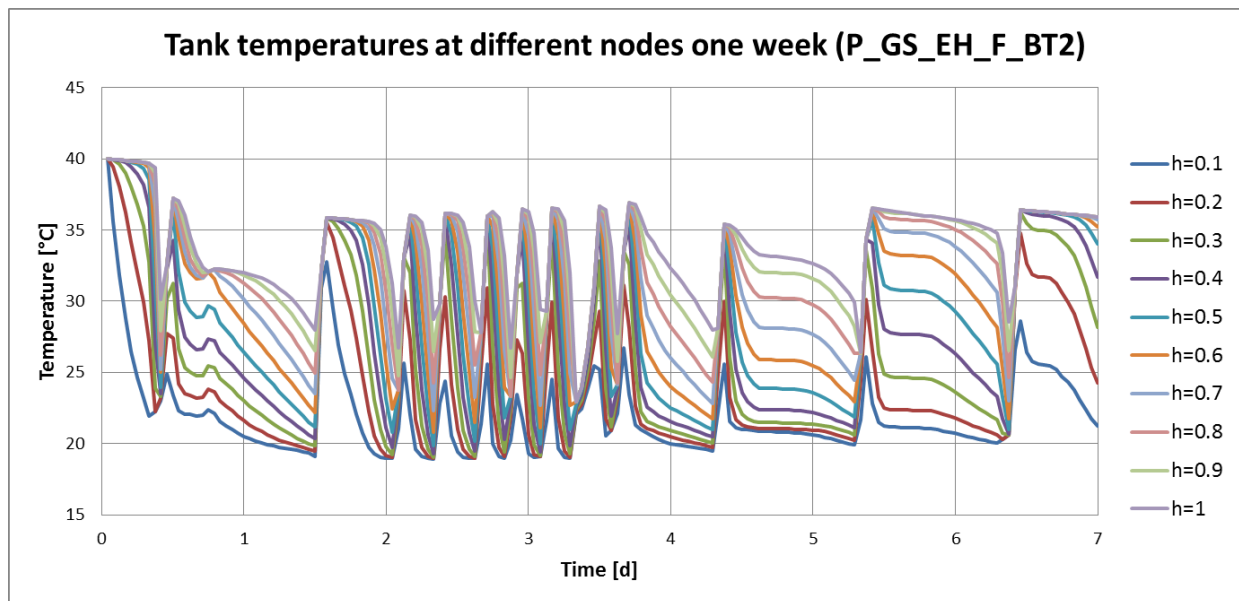


Figure 44 Tank temperatures at different nodes one week (P_GS_EH_F_BT2)

Conclusion

This investigation with different tank layout shows that the tank itself and layout have a big influence on the costs and the decision of which system to take. Furthermore this section shows another strength of this simulation tool. The optimal tank layout can be found by an analysis of different tank layouts. For the further work, it is important that the tank layouts are chosen carefully.

4.3.4 Impact Tank Size

The SimTool offers the possibility to investigate the impact of different tank sizes of the two tanks. To investigate this impact, 2000 L, 4000 L (default) and 8000 L tanks are simulated using the P_GS_EH_F_BT1 model.

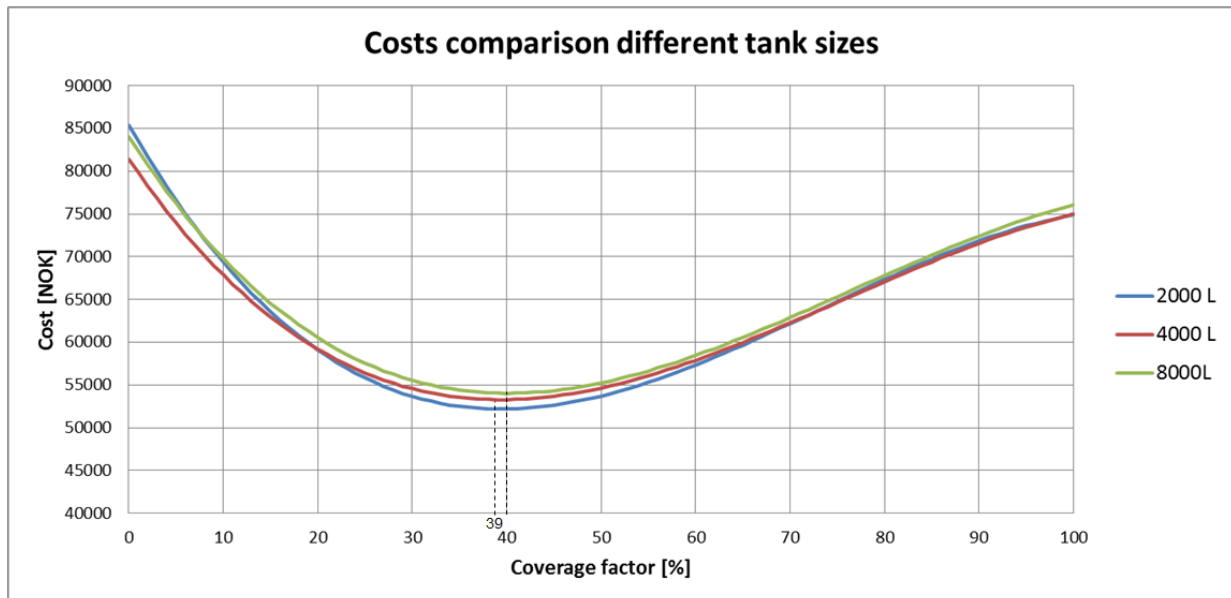


Figure 45: Cost comparison different tank sizes

Discussion

Figure 45 show that the different size of the tank has no big influence on the total costs and the OCF of the whole system. Especially the influence of the different investment costs is relatively low compared to the costs of the whole system. The costs of the different tanks represent 1 % and 2.5% of the total investment costs for the 2000 L or 8000 L tank respectively. Higher thermal losses due to bigger surface also influence total costs. Those losses are shown in Figure 46 where it is to see that they are more than doubled from a 2000 L tank to an 8000 L tank.

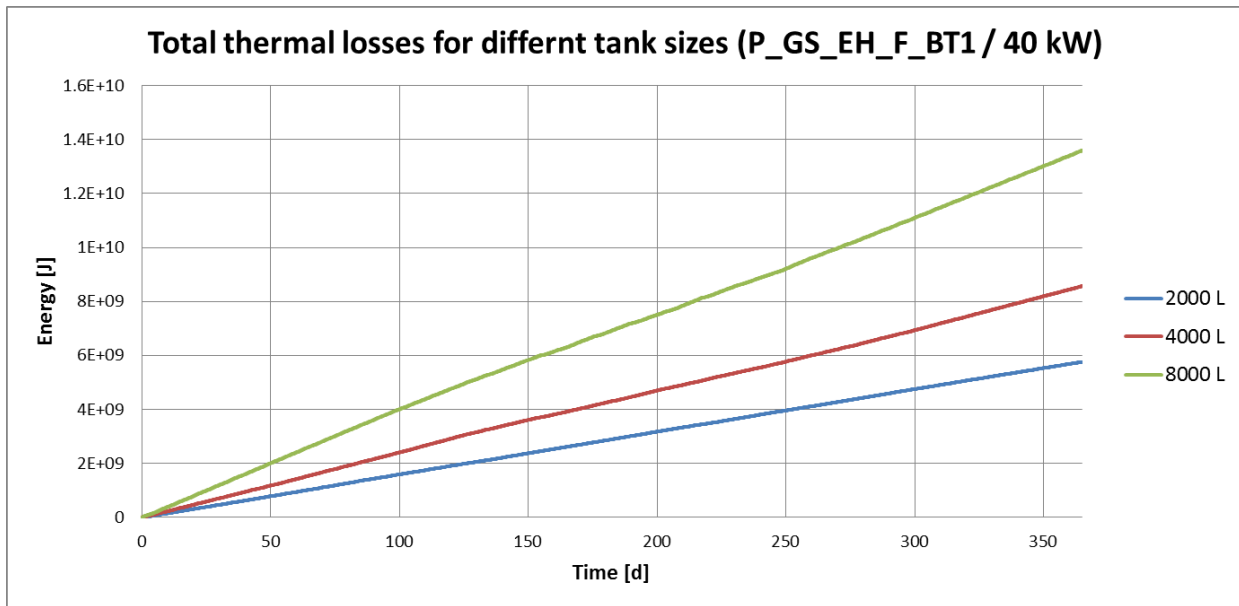


Figure 46: Total thermal losses for different tank sizes (P_GS_EH_F_BT1 / 40 kW)

But a bigger tank has some great advantages as well; these are shown in Figure 47 and Figure 48. Figure 47 shows the HP control over one week and it is to see that the HP in the 8000 L system has an average runtime of 6 hours, the one in the 4000 L system one of 3 hours and the one in the 2000 L system one of 1 hour. Since long HP cycles are favourable, a bigger tank can improve the performance of the system. The duration curve (Figure 48) shows that the HP connected with a big tank delivers the maximal power for a longer time, where the smaller tank has fewer hours on maximal power. The BUH-power cannot be eliminated completely due to the unimproved load control of the tank shown in section 4.1.5.

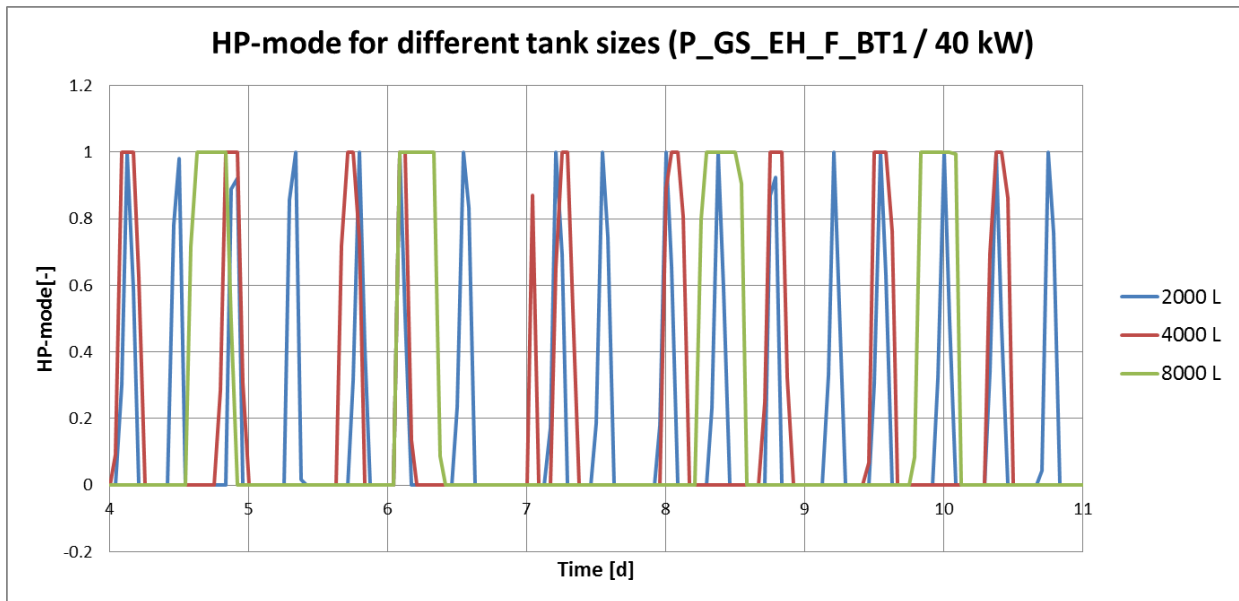


Figure 47: HP-mode for different tank sizes (P_GS_EH_F_BT1 / 40 kW)

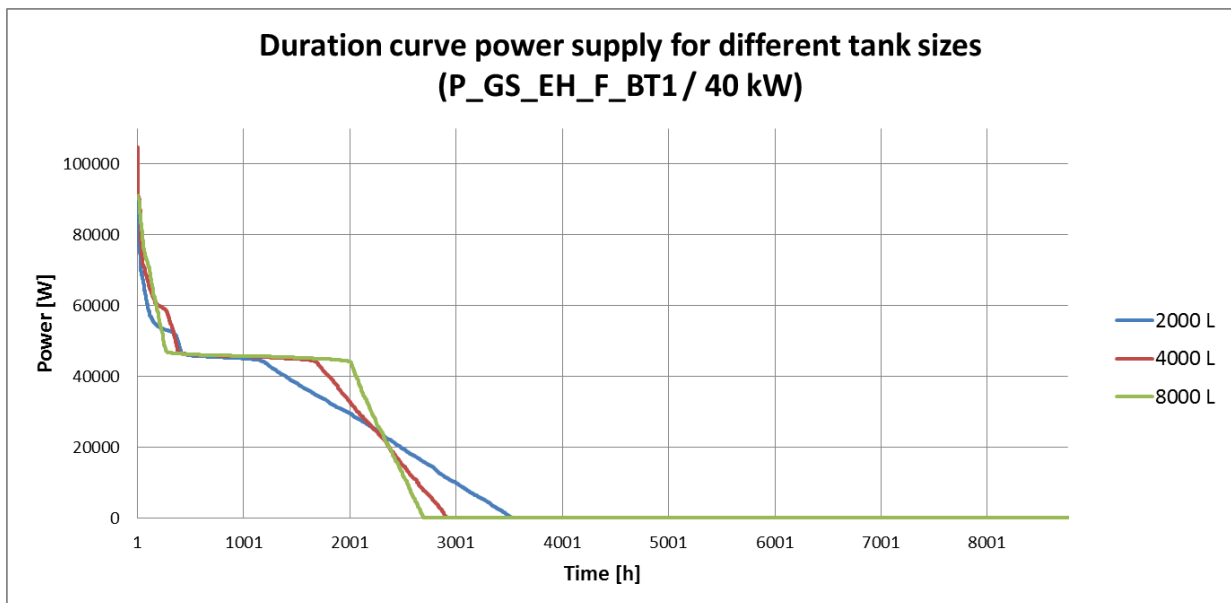


Figure 48: Duration curve energy supply for different tank sizes (P_GS_EH_F_BT1 / 40 kW)

Conclusion

The investigation on different tank sizes shows one of the strengths of this SimTool, namely that the different components can be investigated precisely and the results can be used for an exact design of the building heating system. Furthermore it is possible to investigate different kinds of load and control strategies of the tanks and their impact on the total system.

4.3.5 Impact tank control system

There are two different tank control systems examined in this work which are described in section 3.2.2.3 of this report. The model used for this analysis is the P_GS_EH_F_BT1.

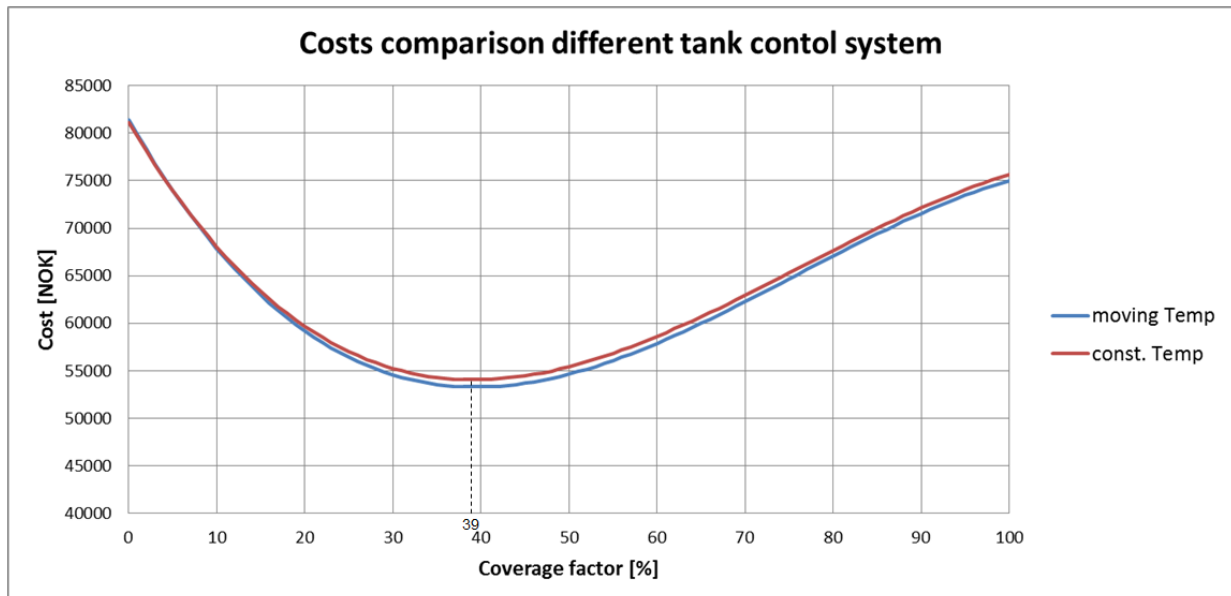


Figure 49: Cost comparison different tank control systems

Discussion

The cost comparison for the two control strategies in Figure 49 shows that the control system has no big influence on the total costs as well as the optimal coverage factor. The reason for the slightly higher costs is the higher energy demand of the heating-tank which is due to the higher temperature level. The duration curve in Figure 49 shows the change in the power supply of the heating-tank. The heating-tank with constant temperature control is consuming slightly more energy on both the HP and the BUH side.

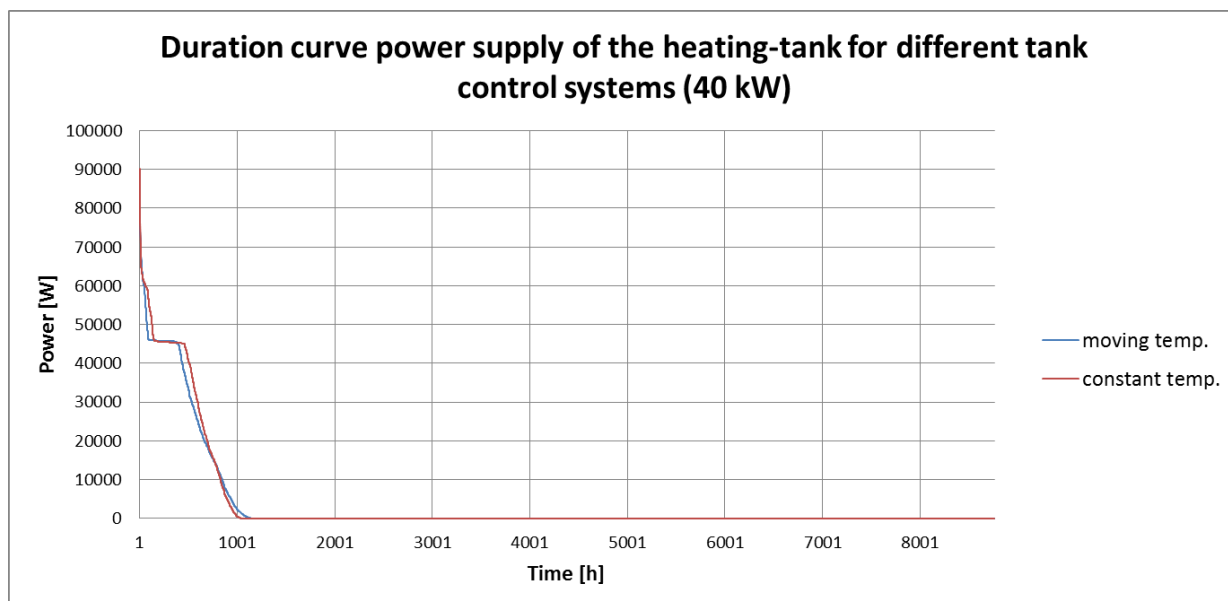


Figure 50: Duration curve power supply of the heating-tank for different tank control systems (40 kW)

Conclusion

The possibility to investigate different tank control systems is not that important to have at the first stage of a heating-tank decision, since there are still too many uncertainties regarding their impact. But if this tool will be used to design the whole system based on energetic points of view, it might be nice to take the opportunity to analyse the whole system more closely.

4.3.6 Impact emission system

The SimTool has two different emission systems implemented; the influences on the system performance and the total costs are analysed in this section using the P_GS_EH_F_BT1 system and the P_GS_EH_RL_BT1 system.

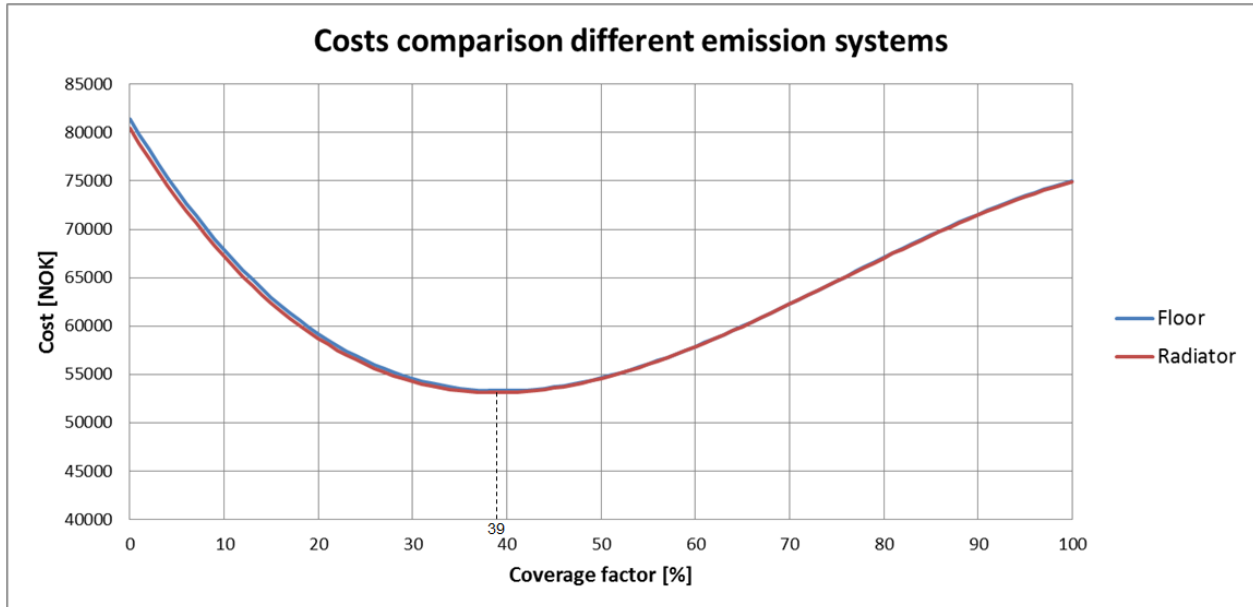


Figure 51: Cost comparison for different emission systems

Discussion

Figure 51 shows that the total costs as well as the OCF stay the same for the two different systems. The investment costs of the radiator system are slightly lower than the investment costs of the floor system. This difference is compensated by the power consumption of the two systems. Since the heating tank temperatures are higher for the radiator system the power consumption of the heating tank raises as well. The course of heating-tank temperatures at the top over two weeks is shown in Figure 52 and the duration curve of the power supply is shown in Figure 53.

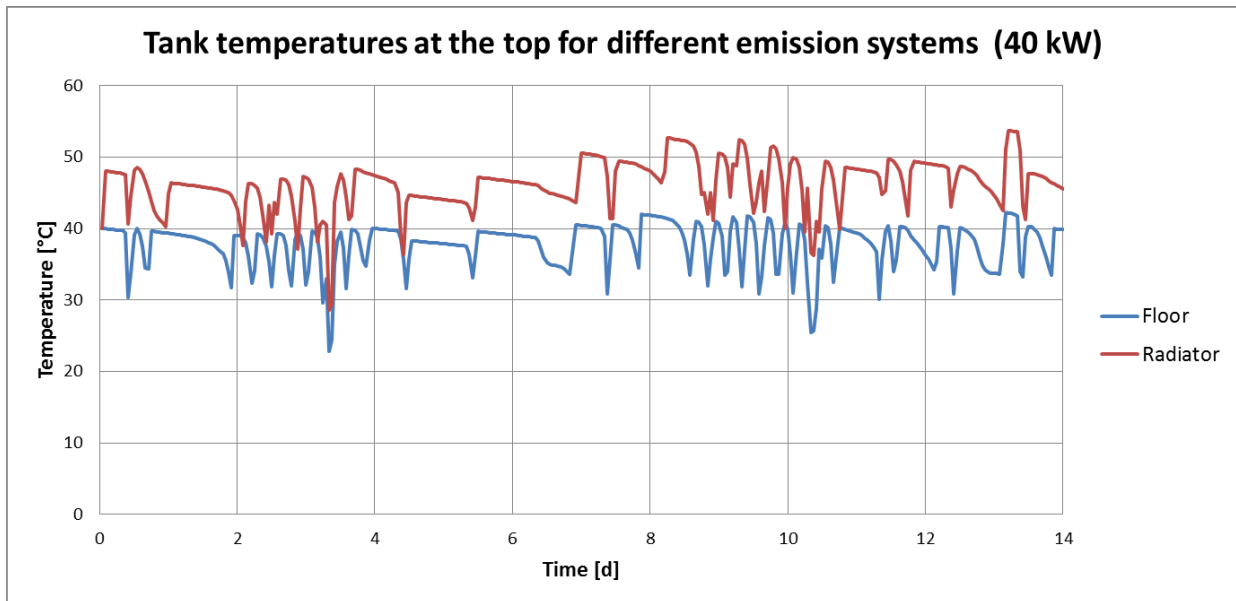


Figure 52: Tank temperatures at the top for different emission systems

The duration curve annual power consumption of the heating-tank shown in Figure 53 shows slightly higher power consumption for the radiator system. The additional power is delivered from the HP as well as the BUH. Beside this small difference, the two curves are quite similar.

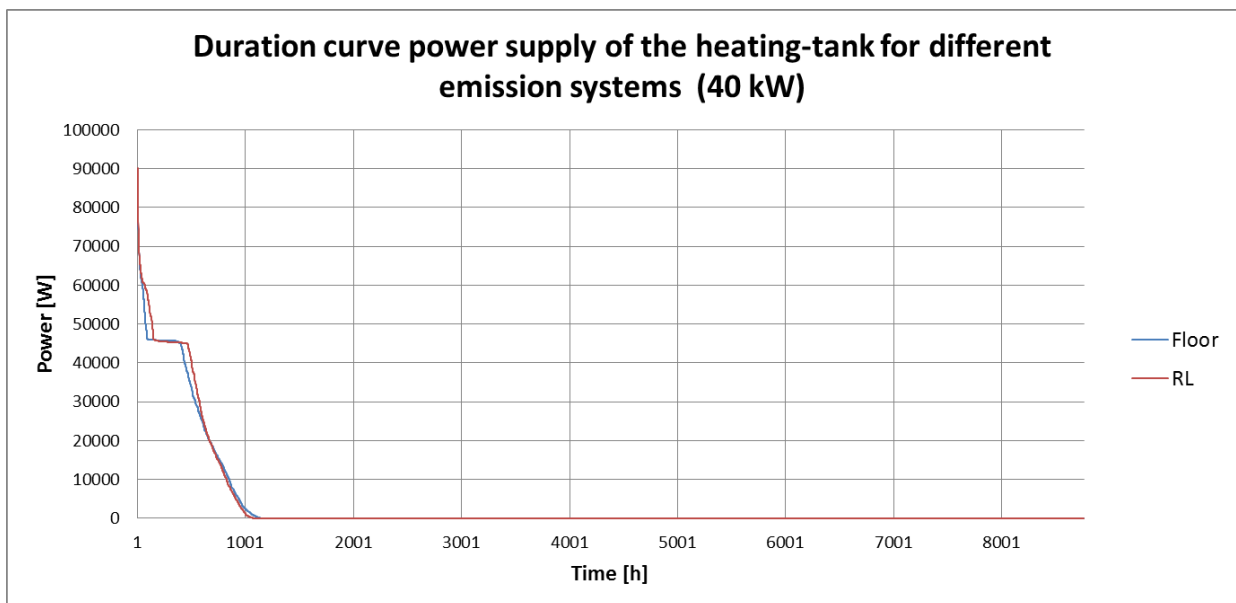


Figure 53: Duration curve power supply of the heating-tank for different emission systems (40 kW)

Conclusion

The emission system has no influence on the decision for a system on costs basis and just a really small influence on the power delivered to the heating-tank. Nevertheless it is interesting from a technical point of view to see the influence of the different emission systems on the whole building heating system. For this kind of investigation other emission systems like TABS or cooling coils need to be applied in the Simulink model.

4.3.7 Impact ground temperatures

In this section the impact of different ground temperatures on the system is investigated. The temperatures were changed in the Simulink model by changing the block input “Average annual outdoor temperature”. This is likely not the smartest way to do it but as mention in section 3.2.6 the ground source model was deeply investigated in another work.

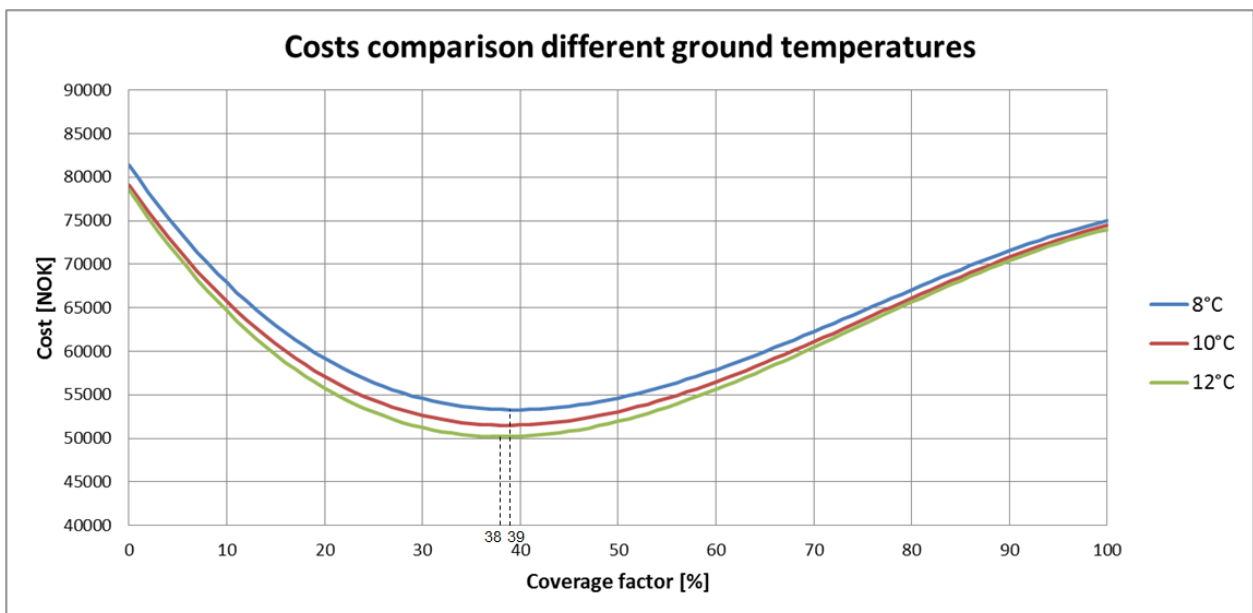


Figure 54: Cost comparison for different ground temperatures

Discussion

The different source temperatures have just a small impact on the costs and no impact on the OCF as shown in Figure 54. The higher costs are due to the better performance of the HP at higher source temperatures. Figure 55 shows the monthly average of the inlet

temperature of the HP for different ground temperatures. One can also see the higher average temperature during the summer; the reason therefore is, as already mentioned in section 4.1.4, the free cooling.

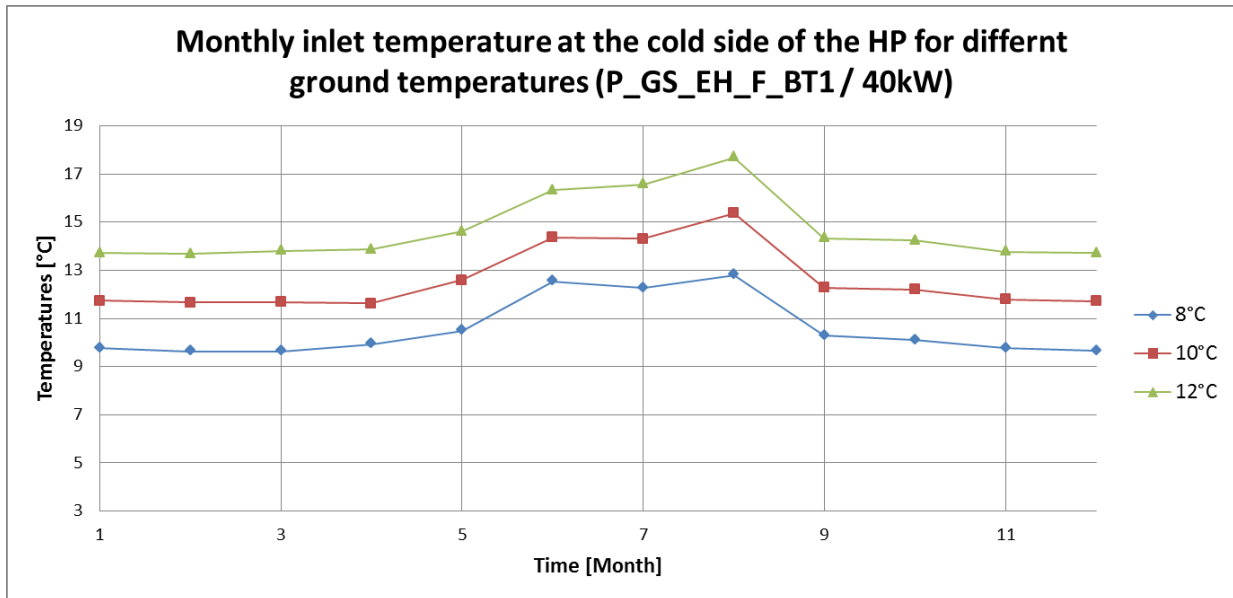


Figure 55: Monthly inlet temperature at the cold side of the HP for different ground temperatures (P_GS_EH_F_BT1 / 40 kW)

The influence of the higher source temperature on the HP is shown in Figure 56 where the monthly average of the COP and the SPF are shown. It is to see, that the COP is related directly to the source temperatures, where the SPF is varying more. This is due to the fact, that SPF includes everything happening in the system, whereas the COP is just balancing the HP. Nevertheless the annual average shown in appendix 2 is bigger for higher source temperatures.

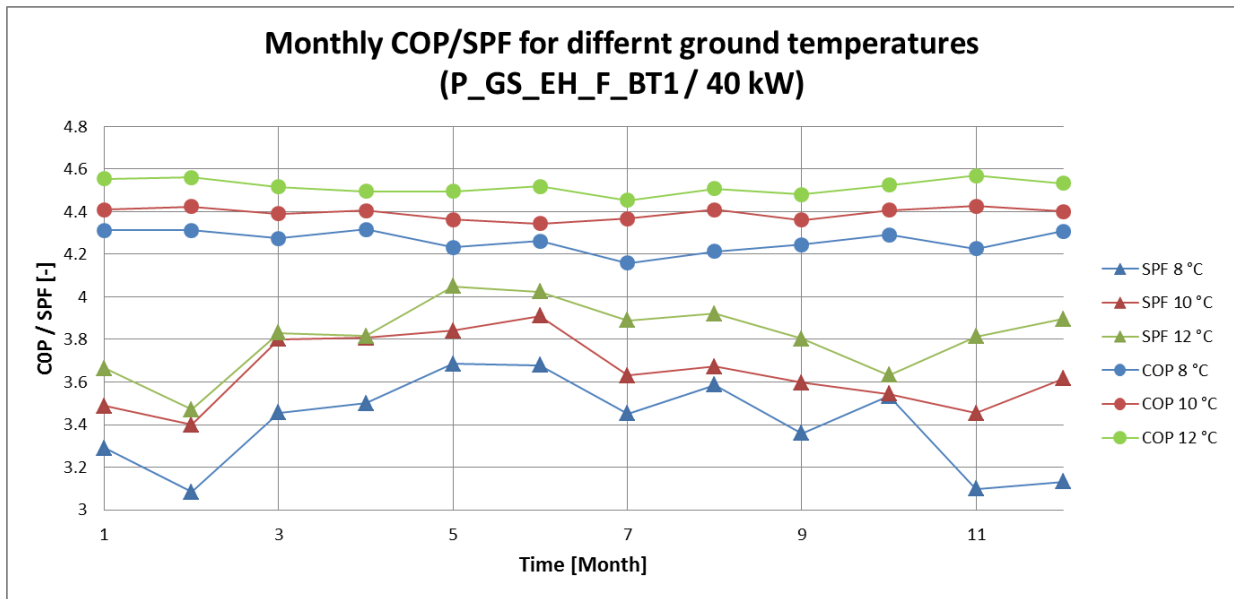


Figure 56: Monthly COP / SPF for different ground temperatures (P_GS_EH_F_BT1 / 40 kW)

Conclusion

The temperature of the ground source model has an impact on the costs, but it just shifts them up or down so it does not have a big influence on the selection of the system combination for the building heating system based on the OCF. Still there is an influence on the whole system by the higher source temperature of the HP. Since the GSM is a black box in this model, it is important to consider the results of Mikkel Ytterhus's thesis to this simulation tool.

4.3.8 Impact DHW-Profile

In this section the impact of different DHW-load profiles on the system is analysed. There is a comparison between the exact profile and an average profile, both shown in section 3.3.2 of this thesis. The course of the total annual costs is shown in Figure 57.

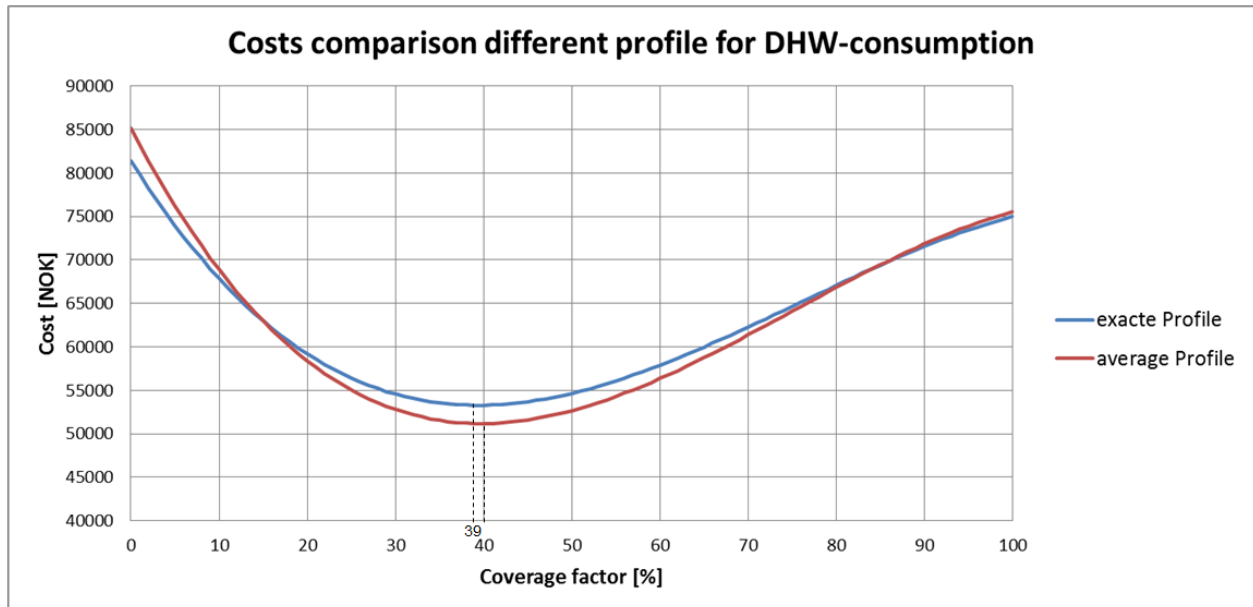


Figure 57: Cost comparison different profile for DHW-consumption

Discussion

The OCF stays more or less the same for both input profiles; on the other hand the costs are varying more (around 2000 NOK). Since both systems have the same cost values implemented, this is an indicator for different power consumption. Therefore the duration curves of the power consumption at the DHW-tank are illustrated in Figure 58. The exact profile leads to a higher BUH power consumption which is needed to cover the peaks of the input. Using the average input profile this power is delivered by the HP.

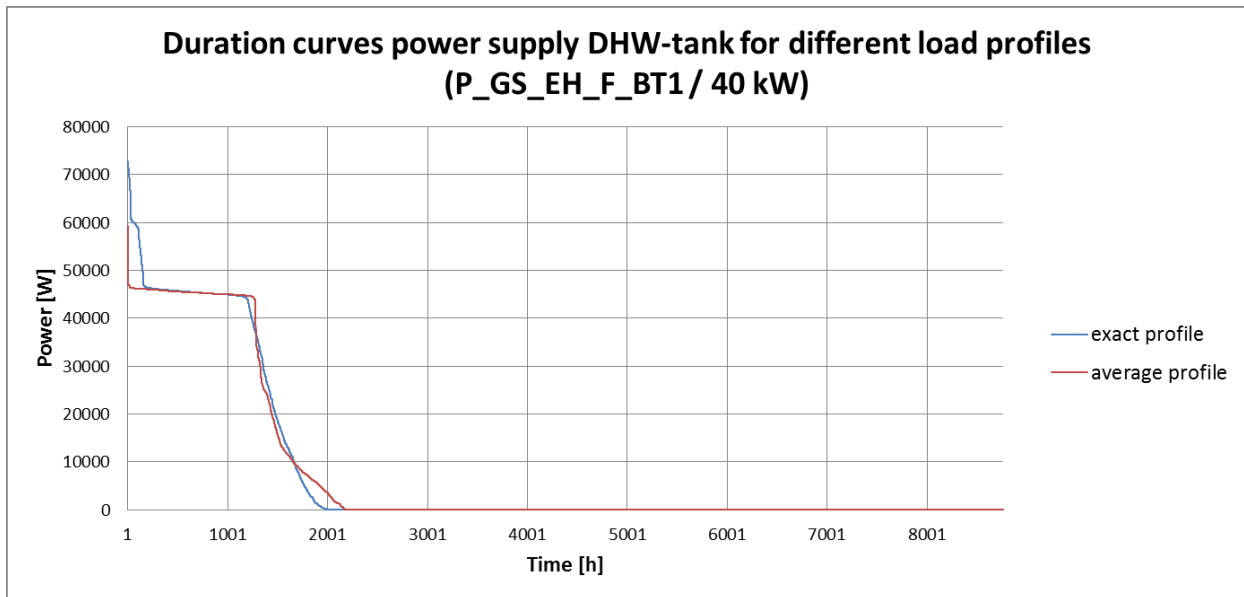


Figure 58: Duration curves power supply DHW-tank for different load profiles (P_GS_EH_F_BT1 / 40 kW)

Conclusion

This investigation shows that the load profile affects the power consumption in the DHW-tank and that this 4000 L tank is not able to compensate jumps in the DHW consumption. As a result of this analysis it can be said that it is recommended to use the exact profiles if they are available.

4.3.9 Impact Cost Parameters

Until now there were just studies about the system performance and the influence of the components, but one of the biggest uncertainties in planning a building heating system is the costs for the different components. For the analysis of the components the default values defined in the previous thesis were taken. By doing critical literature research on these parameters, a certain range for the price of each component was found. Using these new values, new results were generated by changing either the investment cost parameters or the operation cost parameters. The parameters taken for this analysis are shown in appendix 1.

Discussion

Figure 59 shows the total costs over the coverage factor. There it is visible, that the cost parameters have a big influence on the total cost as well as the OCF. On one side, high investment costs will increase the total costs while lowering the OCF. On the other side, high energy costs will increase the total costs as well as the OCF.

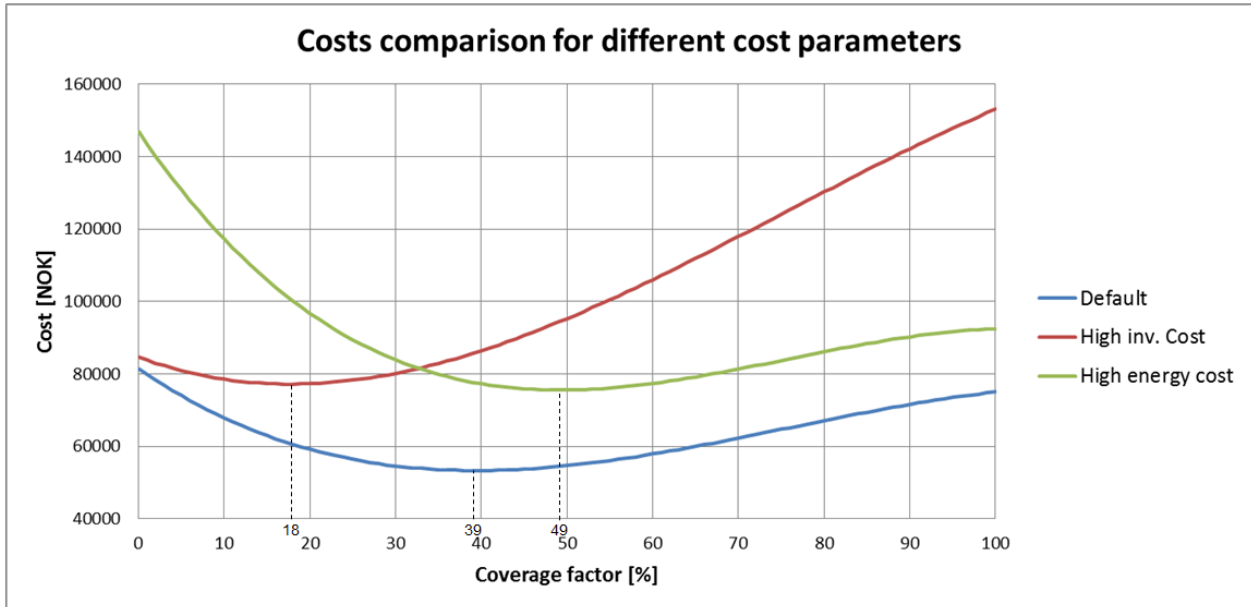


Figure 59: Cost comparison for different cost parameters

Conclusion

This analysis shows that even a small change in the cost parameters has a big influence on the total costs and the optimal coverage factor. If we compare cost parameter changes to the changes caused by different components, we can recognize that the cost parameters have a high influence on the decision for one system. This fact leads to the conclusion that an early decision tool needs to be very accurate on the cost side but can be less accurate on the system side. But for a deeper study and the design of the whole system, it is the important to have a more exact and complex hydraulic system like the one implemented in this tool.

4.4 Air source heat pump

The “Carnot toolbox” has no reversible HP implemented; therefore the idea was to have two HP’s where one delivers the heating power (HP_heat) and the other one delivers the cooling power (HP_cool). The system to switch between those two HP’s is implemented manually by guiding the THB vector either to the HP_heat or the HP_cool. There are also two different heating mixer (see section 3.2.9) implemented. One is working during the heating period, the other one is running during the cooling period.

The model created in this thesis was not running at the end. When the system is switching from heating to cooling mode there are some errors in the model and the whole simulation will stop. This section includes a summary of the errors and some possible reasons for them; at the end some possibilities to solve those problems are mentioned. For the discussion and the conclusion always the results with the 12.5 kW HP were used since this is the simulation which is responsible for the stop of the simulation. The output data is saved in the folder which comes with this thesis.

Discussion

The simulation is running properly until the system is changing from heating to cooling mode ($1.1 \cdot 10^7$ s). Then the HP_cool starts and should cool down the heating tank. The entering fluid of the electric heater which represents the emission system (see section 3.2.9) has unrealistic temperatures (1450 °C) at this point. This is finally the reason for the stop of the simulation. These temperatures lead to “divisions by zero” in the electric heater which is then stopping the simulation. The vector of the electric heater is created in the heating mixer. That could probably be the place where the problem comes from. Furthermore the results are showing, that the inlet and outlet temperatures of the HP_cool are 0.7 °C respectively 0.5 °C and like this really unrealistic. That indicates uncertainties in the performance of the HP_cool what can be another possibility for the problems.

Conclusion

During this thesis it was not possible to figure out the reason for problems. There are two main ways to proceed with this situation, one is to investigate the simulation model used in this thesis and try to solve these problems. This approach includes many uncertainties since there is no proof of the combinations of two HP's to implement the 4-way valve. Nevertheless, some points which could be investigated are listed below.

- Function of the heating mixer for the cooling
- HP input data for the HP_cool
- System control (switch between the two HP's)

The other way is to include an advanced HP model into the simulation; this can be either done by transferring it from another platform (e.g. Modelica by using FMI). Or the HP model included in the "Carnot toolbox" can be adapted so that it is able to run reversibly. For further work, it is recommended to implement a new model.

5 Conclusion

The SimTool has implemented the improvements mentioned in the project description and enables, the user to investigate the hydraulics of a building heating system. For the analyses examined during this project, some rough assumptions for the default values were taken; nevertheless the results are interesting and show the different aspects of a building heating system. The results are already discussed in section 4 of this thesis; the objective of this section is to combine them and to point out the main findings.

The proof of the SimTool was performed using the P_GS_EH_F_BT1 model. The system is able to deliver the power and the temperatures required for the heating system and the DHW-system. Furthermore, it is proven that the tank control works and that the HP performance is similar to the input data. Using the duration curves, the share between power delivered by the HP and power delivered by the BUH is shown. The main conclusion out of this analysis is that the model maps the real system correctly. Nevertheless, all the system parameters used for the simulation are not validated and need to be investigated on the further approach of the SimTool.

The comparison with the results of the previous thesis is show that both simulation tools create similar results where the difference can be declared. Also the rules of thumb for building heating system in Norway are fulfilled for the SimTool.

The analysis of the impact of different components and control system shows some interesting results. The main finding is that the cost based selection of the best system is strongly dependant on the cost parameters, whereas the influence of different components is not that big. But if the selection is not just cost based and energetic aspects such as HP performance tank losses are taken into account as well, it is really important to investigate the hydraulic system. In this area, the tank size and its layout have a large influence on the HP as well as the system performance.

As mentioned earlier in this report, the Simulink model runs on small time steps which lead to long simulation times. The annual simulation of one model takes about 20 hours, depending on which model is chosen. Keeping in mind that several simulations have to be performed to create the cost curve for different coverage factors, one simulation can easily take up to two days

The simulation tool has still some limitation on the HP and the GSM model as well as the intelligent system control, those are points which should be implemented for the final version of the simulation tool. The section 6 contains a listing of possibilities for the further approach on the simulation tool.

6 Further work

The SimTool which is presented in this thesis has many strengths for the investigation of a BHS; nevertheless not everything has been proven and tested yet. This section contains a proposal for the further approach on this simulation tool. The listed points are just recommendations and can be extended or passed over.

Field of improvement	Description
Heat pump	The HP-model should be improved in a way that it is possible to run the HP on various speed. There are several approaches to get a various speed HP model. The various speed HP can be imported from Modelica using the FMI tool or it is also possible to introduce part load parameters and implement them into Simulink.
ASHP	The ASHP model has to be investigated. As already mention in section 0 it is recommended to solve this task by using a new HP model. This improvement can be combined with the development of the various speed HP.
Ground source model	The results of Mikkel Ytterhus's project work should be implemented in this simulation tool, either by setting proven input parameters for the GSM or by importing a new model from another software (FMI-tool).
Pressure drop / Pipes	The pressure drop and the heat loses in the pipes are not implemented in this simulation tool, but there is the possibility to implement them by using a predefined Carnot block.

Emission system	The emission system implemented in this tool is really simple and does not include any ventilation or cooling and heating coils. Since those heating elements are widely used in offices buildings they should be implemented as well. It is also a possibility to introduce TABS and other heating and cooling technologies.
Tank variation	Since the tank model implemented in this model is simple to change, different tank layouts and the influence on the system performance should be investigated.
Simulation time	It would be nice to shorten the run time of the simulation. One possibility is to exchange the most time-consuming elements by simpler models.
Validation parameter	The different parameters taken for the simulation need to be proven by either performing a sensitive analysis on them or by doing research on the state of art values.
Graphical User Interfaces	Matlab offers the opportunity to create Graphical User Interfaces. For the final version this should be implemented to create a user-friendly tool where it is possible to define all the inputs needed.

Table 14: Further work

7 Reflexion

The main goal of this work was to improve the Simulation tool created in a previous thesis. The SimTool represents the next step to the final version of an “Early decision tool for the building integration of HP’s”; it includes a hydraulic model of the BHS with all the main components. Using the SimTool it is possible to analyse the hydraulic system as well as the costs and CO₂ emissions of each layout. The output of this thesis corresponds with the defined task, nevertheless there were some stumbling blocks during the work.

The initial plan was to implement a various speed HP model from Modelica into Matlab/Simulink. But developing the Matlab/Simulink model of the BHS took longer than estimated, so there was not enough time left for this topic. In agreement with the supervisor I took the decision to stay with the on-off HP model from the “Carnot toolbox” for my system and to set the improvement of the HP model as a further task. This decision affected the ASHP model as well, since I was not able to implement the 4-way valve using the simplified HP model. Furthermore I wasn’t able to reduce the simulation time so I wasn’t able to perform all the different system combinations mentioned in the section 3.1 of this thesis. This fact has led us to the decision that I should compare the influence of the different components to a base system.

Despite this entire problem it was a very interesting and challenging task with a lot of new aspects for me. I learned a lot about the modelling in Matlab/Simulink and the coupling of Simulink with Matlab. Besides I experienced a new culture and new technical standards here in Norway. I hope that my effort will help to bring this simulation tool closer to completion and that it can be used by customers soon.

7.1 *Expenditure of time*

This section will give a short overview over the expenditure of time for this thesis. During the whole project I kept a working journal where I noted the daily working hours as well as the topic I was working on. The progress of the work and the time I was working on each task is shown in Figure 60. Between the different tasks there was a smooth transition nevertheless the graph represents quite exactly the time I was working on those topics.

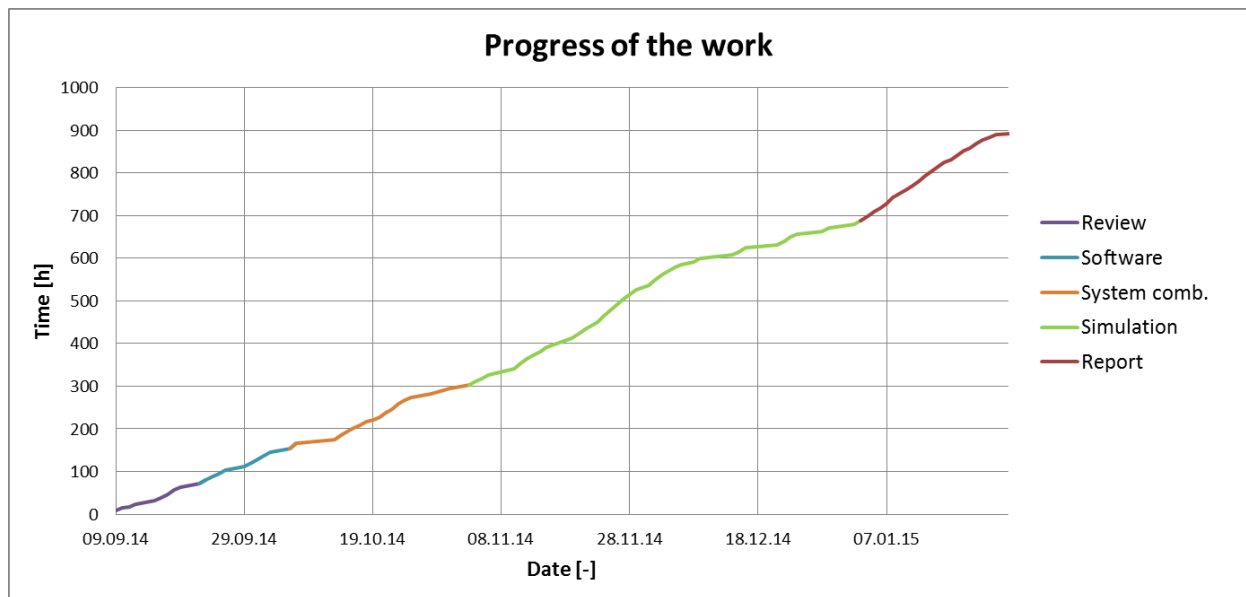


Figure 60: Progress of the work

7.2 Expression of thanks

I want to thank everyone who supported me during my work on my thesis:

- My supervisors L. Georges, M. J. Alonso and T. M. Eikevik for the technical support during the whole project.
- M. Ytterhus for translating the summary to Norwegian.
- C. Wemhöner for his effort for making me possible to write my thesis abroad and his support on the “Carnot toolbox”.
- W. Tegethoff and TLK-thermo for their support with the FMI Suite.
- M. Soriano for the grammatical correction and M. Keusch for the technical review of my report.

8 Source

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Appendix

The appendices A1 – A4 are included in this printed report, the other appendices are saved in the project folder.

- A1. Input parameters
- A2. Summary simulation results
- A3. Duration curves
- A4. Various plots
- A5. Characteristic curves HP (project folder)
- A6. Research plan (project folder)
- A7. Timetable (project folder)
- A8. Working journal (project folder)

A1. Input Parameters

All the parameters used during the simulation are listed and referenced here. There are several cost parameters in brackets; those are the one used for the analysis of the cost parameters. The term used for referencing of the values is shown below.

M: Default values form Carnot blocks

C: Chosen parameters during discussions with the supervisors

P: Values taken from the previous thesis

R: Parameters found in literature research (references are listed below)

Description	Unit	Value	Source
Heat pump			
thermal capacity hot loop	J/K	80000	M
thermal capacity cold loop	J/K	50000	M
heat loss coefficient	W/K	7	M
Cold side linear massflow dependant pressure drop in	Pa*s/kg	10	M
Cold side quadratic massflow dependant pressure drop hot side in	Pa*s ² /kg	10	M
Hot side linear massflow dependant pressure drop in	Pa*s/kg	10	M
Hot side quadratic massflow dependant pressure drop hot side in	Pa*s ² /kg	10	M
Tank			
Heat loss coefficient cylinder wall	W/(m ² K)	0.5	M
Heat loss coefficient bottom	W/(m ² K)	0.5	M
Heat loss coefficient top cover	W/(m ² K)	0.5	M
Effective (wall and fluid) vertical conductivity	W/(m*K)	0.05	M
Initial temperature (vector or scalar)	°C	60 / 40	C
Position	-	standing cylinder	C
Number of connections	-	3	M
Number of nodes	-	10	M
Number of measurement points	-	10	M
Electric heater			
nominal heating power	W	50000	C

Bio heater			
nominal heating power	W	50000	C
heat loss coefficient	W/K	3	M
volume of the boiler	m ³	0.02	C
relative power in 0..1	-	[0.25 1]	M
Temperature	°C	[40 70]	M
Efficiency data in 0..1	-	[0.8 0.8; 0.8 0.8]	M
Electric power	W	[20 120]	M
pressure drop linear in massflow	Pa*s/kg	10	M
pressure drop quadratic in massflow	Pa*s ² /kg ²	100	M
initial temperature	°C	20	M
number of nodes	-	1	M
type of fuel	-	solid	C
temperature	°C	20	M
stoichiometric air demand	kg/kg	4.07	R1
pressure	Pa	100000	M
heat without/with condensation	J/kg	[18 20]*1000000	R1
condensation temperature	°C	47	R1
price of fuel per kg	-	1	M
massfraction [H C O S N H ₂ O]	-	[0.062 0.50 0.43 0.0005 0.003 0.0045]	R1
Gas heater			
nominal heating power	W	50000	C
heat loss coefficient	W/K	3	M
volume of the boiler	m ³	0.02	C
relative power in 0..1	-	[0.25 1]	M
Temperature	°C	[40 70]	M
Efficiency data in 0..1	-	[0.8 0.8; 0.8 0.8]	M
Electric power	W	[20 120]	M
pressure drop linear in massflow	Pa*s/kg	10	M
pressure drop quadratic in massflow	Pa*s ² /kg ²	100	M
initial temperature	°C	20	M
number of nodes	-	1	M
type of fuel	-	gaseous	C
temperature	°C	20	M
stoichiometric air demand	kg/kg	17.2	R1
pressure	Pa	100000	M
heat without/with condensation	J/kg	[32 36]*1000000	R1
condensation temperature	°C	-50	R1
price of fuel per kg	-	1	M
massfraction [H C O S N H ₂ O]	-	[0.44 0.25 .25 0.005 0.005 0.05]	R1

Ground Source			
Average annual outdoor temperature	°C	8	C
Temperature gradient	K/m	0.025	M
Thermal conductivity ground	W/m/K	2	M
Heat capacity of the ground	J/kg/K	800	M
Density of the ground	kg/m ³	2500	M
Thermal conductivity filling	W/m/K	1	M
Heat capacity of the filling	J/kg/K	1000	M
Density of the filling	kg/m ³	2000	M
B: probe distance	m	10	M
Diameter of tube	m	0.032	M
Diameter of drilled hole	m	0.18	M
Field geometry	-	5x10	C
Number of parallel tubes	-	50	M
No. of nodes in axial direction	-	10	M
No. of nodes in radial direction	-	10	M
grid factor	-	2.5	M
Heat exchanger			
type of flow (0 = parallel, 0.5 = cross, 1 = counter)	-	1	C
constant heat transfer	W/K	2000	M
\dot{m}_{nom_hot} [kg/s] (>0) , ua_{exp_hot} (>=0)	-	[0.04 0]	M
$[\dot{m}_{nom_cold}$ [kg/s] (>0) , ua_{exp_cold} (>=0)]	-	[0.04 0]	M
heat losses to ambient	W/K	3	M
capacity	J/K	10000	M
Source: pressure drop linear in massflow	Pa*s/kg	20	M
Source: pressure drop quadratic in massflow	Pa*s ² /kg ²	10	M
Load: pressure drop linear in massflow	Pa*s/kg	20	M
Load: pressure drop quadratic in massflow	Pa*s ² /kg ²	10	M
initial temperature	°C	20	M
Design Conditions			
Building size	m ²	2394.2	P
Indoor temperature at DOT winter	°C	20	P
Design outdoor temperature (DOT) winter	°C	-20	P
Indoor temperature at DOT summer	°C	26	P
Design outdoor temperature (DOT) summer	°C	26.7	P
Heating System			
Highest outdoor temperature with heating requirement	°C	17	P
Design temperatures for radiators			
Supply temperature at highest outdoor temperature	°C	29	P
Supply temperature at DOT	°C	60	P
Return temperature at DOT	°C	50	P
Radiator exponent	-	1.3	P

Design temperatures for floor heating			
Supply temperature at highest outdoor temperature	°C	25	P
Supply temperature at DOT	°C	35	P
Return temperature at DOT	°C	30	P
Floor heating exponent	-	1.1	P
Cooling system			
Lowest outdoor temperature with cooling requirement	°C	17	P
Design temperatures for cooling system			
Supply temperature at lowest outdoor temperature	°C	15	P
Supply temperature at DOT	°C	10	P
Return temperature at DOT	°C	15	P
Cooling system exponent	-	1.3	P
Design temperatures for floor cooling			
Supply temperature at lowest outdoor temperature	°C	19	P
Supply temperature at DOT	°C	16	P
Return temperature at DOT	°C	19	P
Floor cooling exponent	-	1.1	P
DHW - system			
inlet temperature DHW	°C	5	C
outlet temperature DHW	°C	45	C
Capital Cost			
Interest rate	-	0.07	P
Heat Pump			
Cost per kW installed heat pump capacity	NOK/kW	6000 (9600)	P (R2)
Life time HP	years	18	P
Heat source/sink			
Cost per meter borehole	NOK/m	280 (800)	P (R2)
Life time energy well	years	50	P
Electric heater			
Cost per kW installed electric heater	NOK/kW	500 (8000)	P (R3)
Life time electric heater	years	15	P
Efficiency electric heater	-	0.9	P
Bio heater			
Cost per kW installed bio heater	NOK/kW	8000	P
Life time bio heater	years	20	P
Efficiency bio heater	-	0.73	P
Natural gas heater			
Cost per kW installed gas heater	NOK/kW	1000	P
Life time gas heater	years	15	P
Efficiency natural gas heater	-	0.8	P

Photovoltaic panels			
Cost per kWp installed photovoltaic	NOK/kWp	25000 (26000)	P (R4)
Annual energy production per installed kWp PV	kWh/kWp	781	P
Life time photovoltaic	years	20	P
How much PV panels (m ²) is needed per kWp	m ₂ /kWp	7.4	P
Buffer tank			
2000 L tank	NOK	15300	R5
4000 L tank	NOK	23175	R5
8000 L tank	NOK	38925	R5
Hydronic heating system with radiators			
Cost radiators	NOK/m ₂	300	P
Life time radiators	years	30	P
Hydronic floor heating/cooling system			
Cost floor heating	NOK/m ₂	400 (630)	P (R6)
Life time floor heating/cooling	years	40	P
Operational cost			
Electricity cost	NOK/kWh	0.8 (1.5)	P (C)
Bio fuel cost	NOK/kWh	0.74	R1
Natural gas cost	NOK/kWh	0.88	P
Maintenance and running cost			
Maintenance cost HP	NOK/inv	0.02	P
Maintenance cost electric heater	NOK/inv	0.005	P
Maintenance cost bio heater	NOK/inv	0.02	P
Maintenance cost gas heater	NOK/inv	0.02	P
Maintenance cost photovoltaic panels	NOK/inv	55	P
Emissions			
Emission from electricity	NOK/inv	395	P
Emissions from bio fuel	NOK/inv	42	R1
Emissions from natural gas	NOK/inv	211	P
Emissions from photovoltaic	NOK/inv	-395	P

R1: Calculation formulae, fuels and parameters. (2013). Retrieved January 19, 2015, from <http://www.testo.ch/>

R2: Gloor, R. (2014). *Wärmepumpe*. Retrieved January 19, 2015, from <http://www.energie.ch/waermepumpe>.

R3: Verkaufspreisliste 2014. (2014). Retrieved January 19, 2015, from http://www.stoeri.com/fileadmin/stoeri_files/downloads/allgemein/stoeri_preislisten_alle.pdf.

R4: Thorud, B. 2014, *Kostnader og Lønnsomhet i et Voksende Solenergimarked*, Solenergidagen

R5: Gross-Pufferspeicher Typ PSG 2500 – 10000 l. (2014). Retrieved January 19, 2015, from <http://www.lorenz-behaelterbau.de/PDF/Grosspuffer.pdf>

R6: Fussbodenheizung. (2014). Retrieved January 19, 2015, from <http://www.systectherm.ch/medias/elektrowarme/fussbodenheizung/pdf/plfussbodenheizung.pdf>.

A2. Summary Simulations Results

This appendix includes the exact results for the simulations performed during the work on the thesis. They should help to understand the discussions and conclusions made in the report. Just the most important results are listed in this paper; the other results are visible in the simulation outputs saved on the data disk.

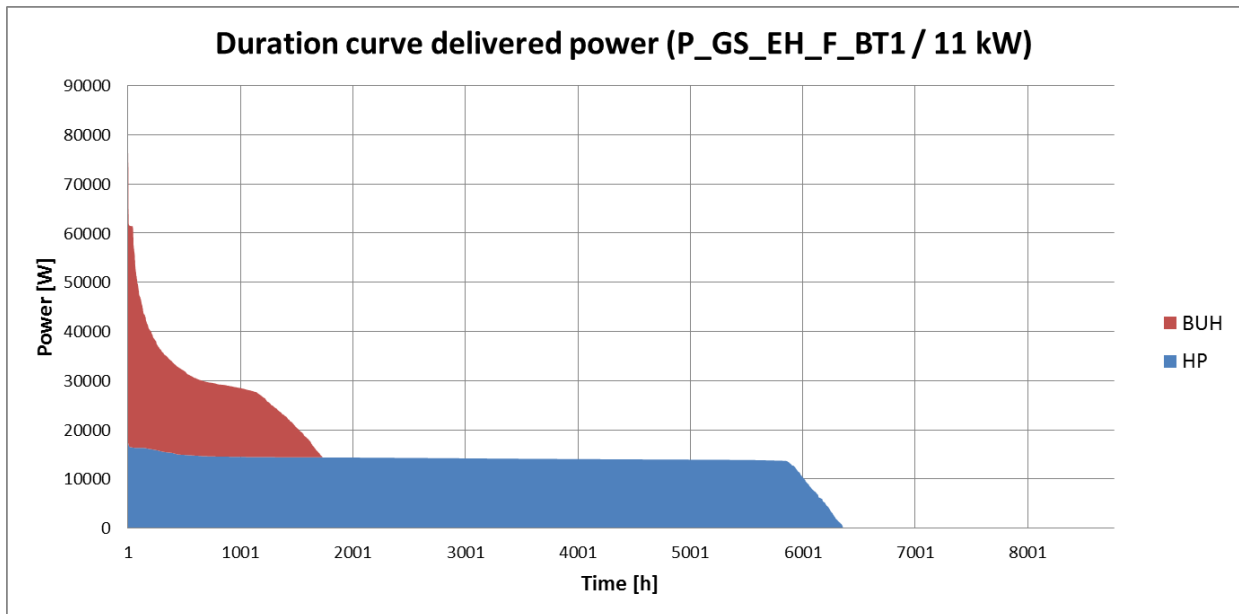
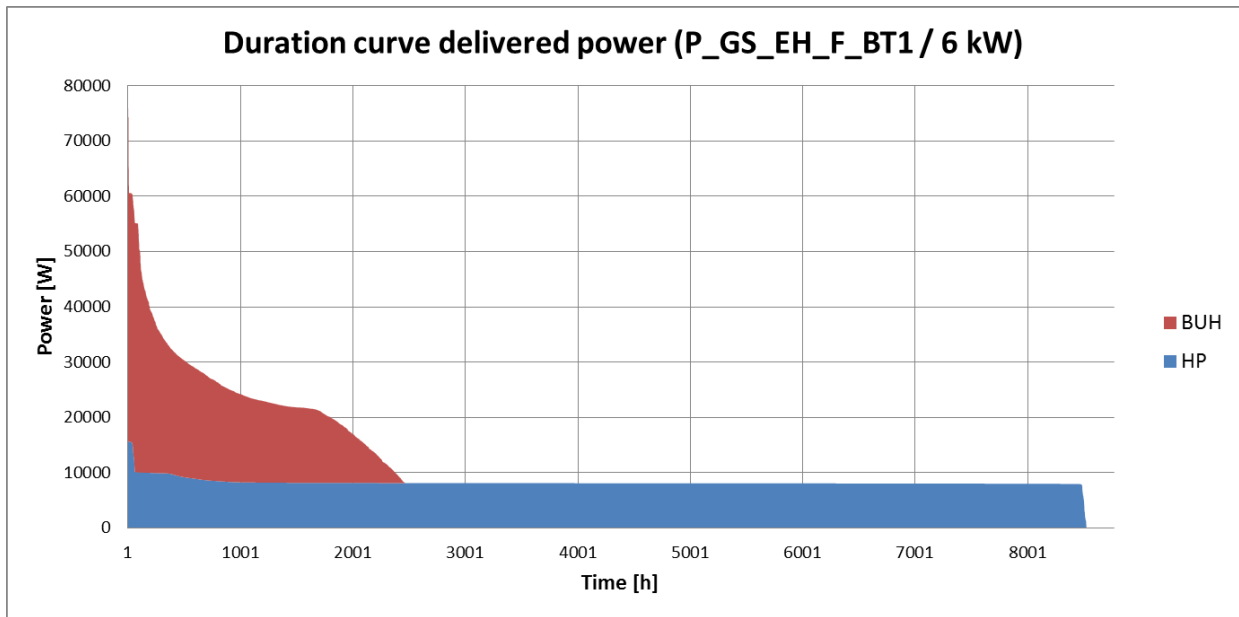
HP-Size [kW]	Coverage factor [%]	Energy coverage [%]	Annual total cost [NOK]	Annual Emissions [gCO ₂]	Average COP [-]	SPF [-]
P_GS_EH_F_BT1						
6	8.0	64.2	68048	24011435	4.48	1.78
11	14.7	80.2	68258	19081124	5.04	2.24
20	26.7	88.4	50621	14647384	4.66	2.92
40	53.3	95.3	59186	12860871	4.27	3.33
50	66.7	99.9	58727	9693531	4.92	4.41
75	100.0	100.0	75158	9891478	4.69	4.32
P_GS_EH_F_BT1_10 °C						
6	8.0	66.2	65925	23146625	4.76	1.85
11	14.7	79.6	65798	18821525	5.25	2.27
20	26.7	89.5	49195	13997273	4.79	3.06
40	53.3	97.3	56977	11872902	4.40	3.60
50	66.7	100.0	57947	9319489	5.06	4.59
75	100.0	100.0	74567	9596616	4.83	4.46
P_GS_EH_F_BT1_12 °C						
6	8.0	67.5	64815	22679953	4.98	1.89
11	14.7	79.9	64720	18356783	5.38	2.33
20	26.7	90.6	47780	13356006	4.91	3.20
40	53.3	98.1	55802	11332779	4.53	3.77
50	66.7	100.0	57341	9023329	5.23	4.74
75	100.0	100.0	74122	9368772	5.00	4.56
P_GS_EH_F_BT1_2000 L						
6	8.0	64.1	69897	24728549	4.53	1.73
11	14.7	79.8	69813	19730726	5.00	2.17
20	26.7	89.3	50235	14484079	4.60	2.95
40	53.3	96.6	58085	12386230	4.22	3.45
50	66.7	99.0	59340	9952615	4.88	4.30
75	100.0	100.0	75314	9954630	4.67	4.30

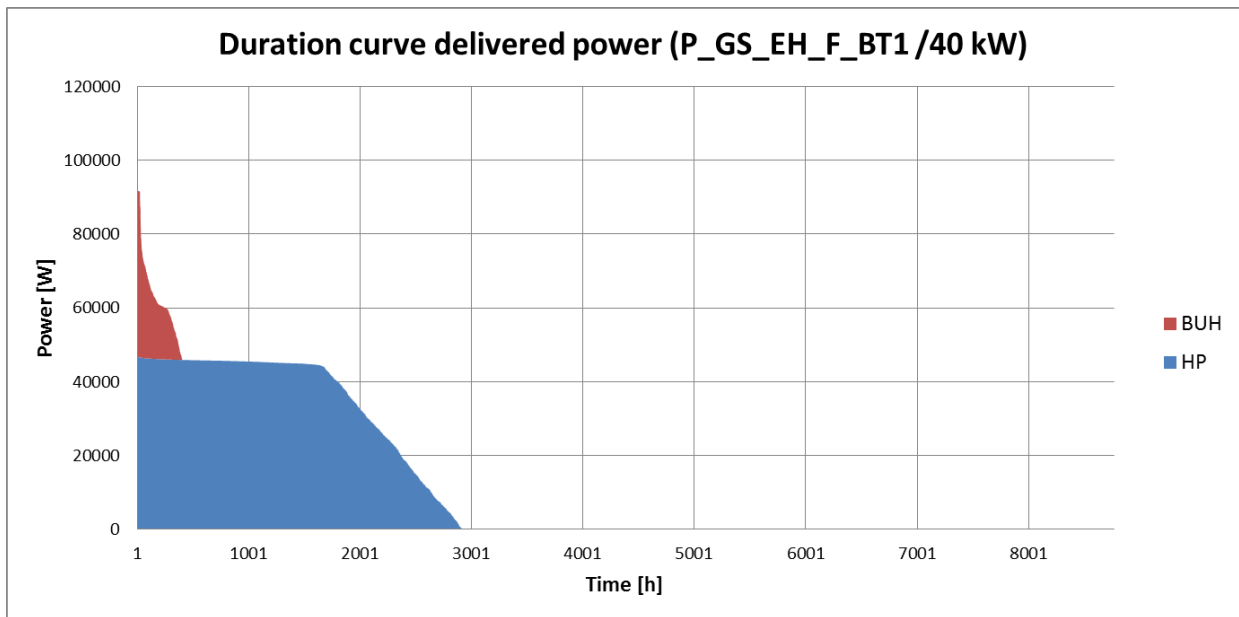
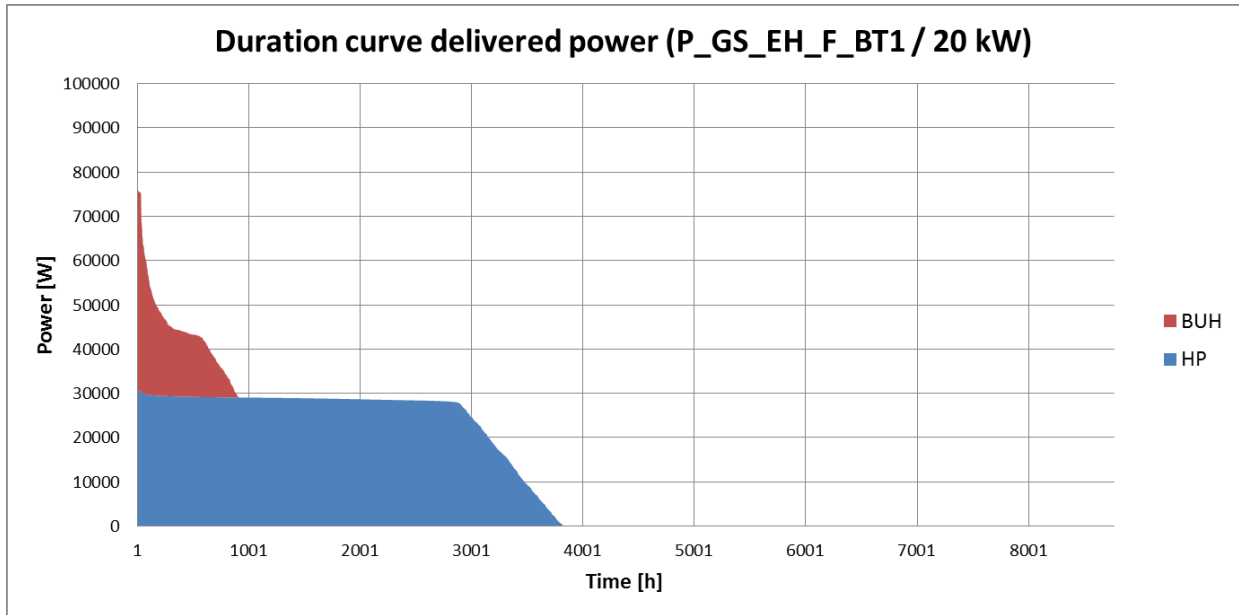
P_GS_EH_F_BT1_8000 L						
6	8.0	62.9	69632	24336059	4.54	1.76
11	14.7	80.5	70654	19329404	4.92	2.21
20	26.7	89.3	51459	14749843	4.61	2.90
40	53.3	96.9	59407	12682203	4.31	3.37
50	66.7	100.0	59644	9814478	4.98	4.36
75	100.0	100.0	76188	10064354	4.67	4.25
P_GS_EH_F_BT1_conts Heating Tank temp						
6	8.0	64.4	68100	24034662	4.47	1.78
11	14.7	81.4	68760	19022815	4.94	2.25
20	26.7	89.1	51214	14941583	4.53	2.86
40	53.3	96.0	59899	13212051	4.17	3.24
50	66.7	100.0	59473	10048408	4.84	4.26
75	100.0	100.0	75782	10193508	4.64	4.20
P_GS_Bio_F_BT1						
6	8.0	64.0	83456	8440662	4.48	1.79
11	14.7	80.2	77846	8736851	5.06	2.24
20	26.7	87.9	76043	9190573	4.66	2.86
40	53.3	95.7	85076	9230628	4.27	3.35
50	66.7	99.9	85701	8955984	4.91	4.39
75	100.0	100.0	102118	9472055	4.70	4.34
P_GS_Gas_F_BT1						
6	8.0	64.0	64313	15816457	4.53	1.79
11	14.7	80.2	56668	13700505	5.06	2.24
20	26.7	88.1	52802	11920227	4.67	2.88
40	53.3	95.6	60842	11468506	4.28	3.34
50	66.7	100.0	60589	9323404	4.91	4.40
75	100.0	100.0	76921	9661918	4.70	4.33
P_GS_EH_F_BT2						
6	8.0	56.1	77395	27595180	4.40	1.55
11	14.7	56.0	72252	28072092	5.58	1.52
20	26.7	67.9	67010	21714921	4.89	1.97
40	53.3	86.5	66124	15852838	4.27	2.70
50	66.7	98.3	60137	10308370	4.92	4.15
75	100.0	100.0	75469	10028583	4.69	4.26
T_GS_EH_F_BT1						
20	15.4	75.1	109859	38229260	4.92	2.10
40	30.8	86.0	122467	28801703	4.36	2.79
50	38.5	94.6	82439	20890010	4.95	3.84
75	57.7	97.4	96297	20037378	4.62	4.01
100	80.0	98.5	117845	22827986	3.87	3.52
130	100.0	99.5	140323	24467132	3.48	3.28

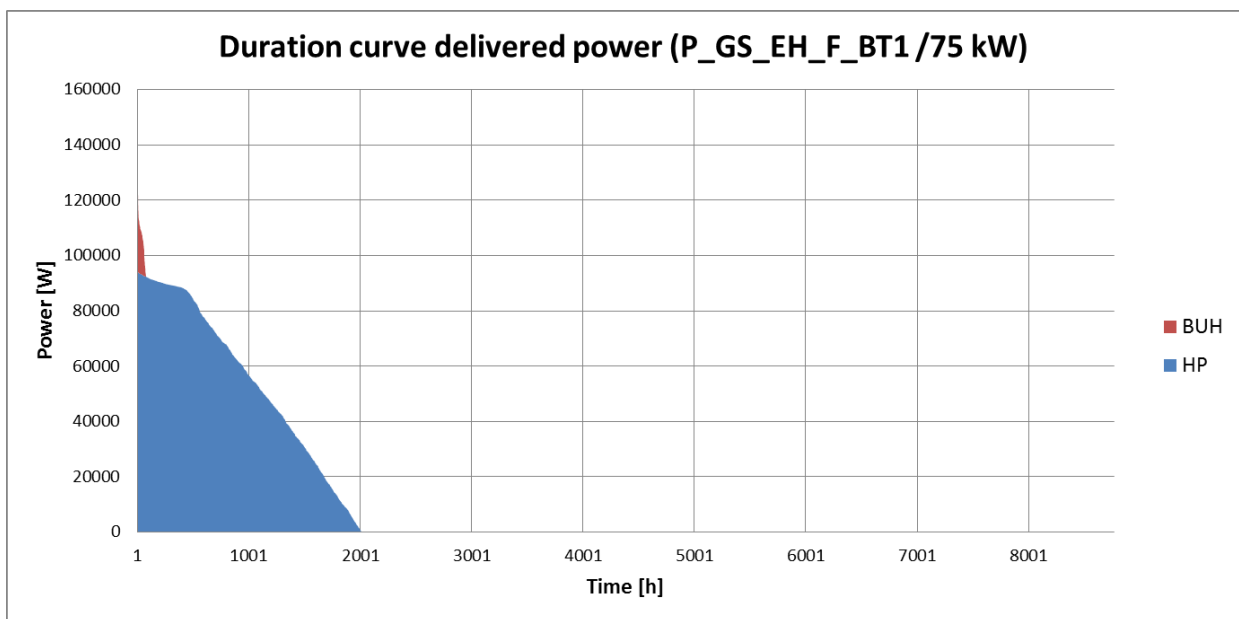
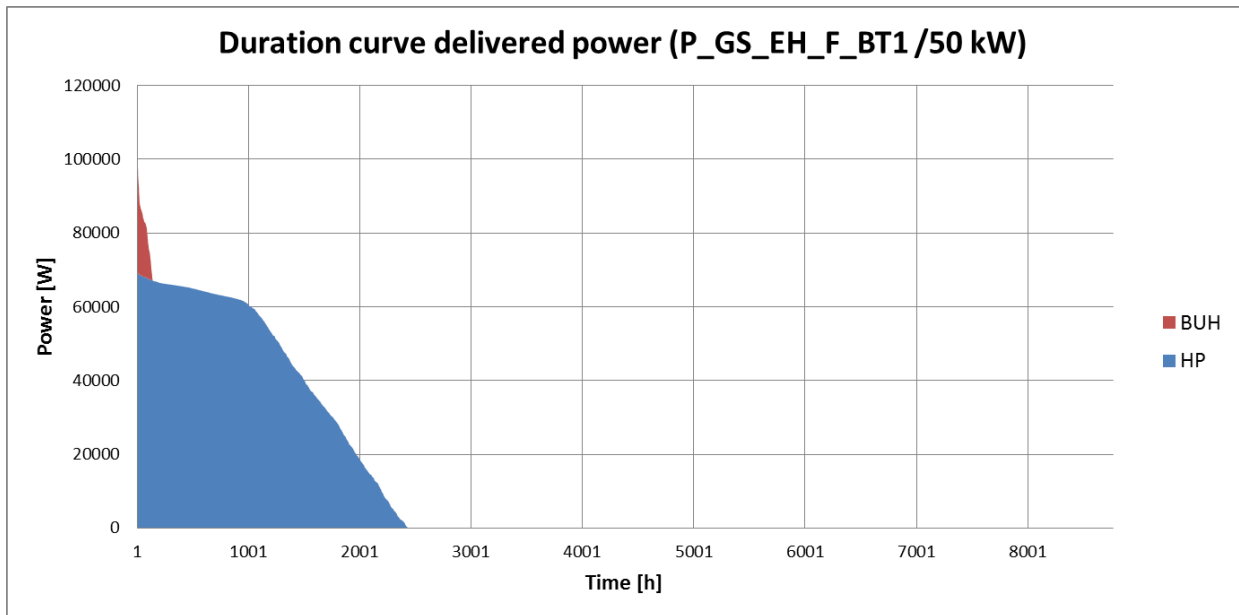
Z_GS_EH_F_BT1						
6	8.0	64.2	68048	0	4.48	1.78
11	14.7	80.2	68258	0	5.04	2.24
20	26.7	88.4	50621	0	4.66	2.92
40	53.3	95.3	59186	0	4.27	3.33
50	66.7	99.9	58727	0	4.92	4.41
75	100.0	100.0	75158	0	4.69	4.32

A3. Duration Curves

In this appendix the duration curves of the power consumption for the P_GS_EH_F_BT1 model are shown for all the different HP-sizes. They show the share between BUH-power to HP-power.



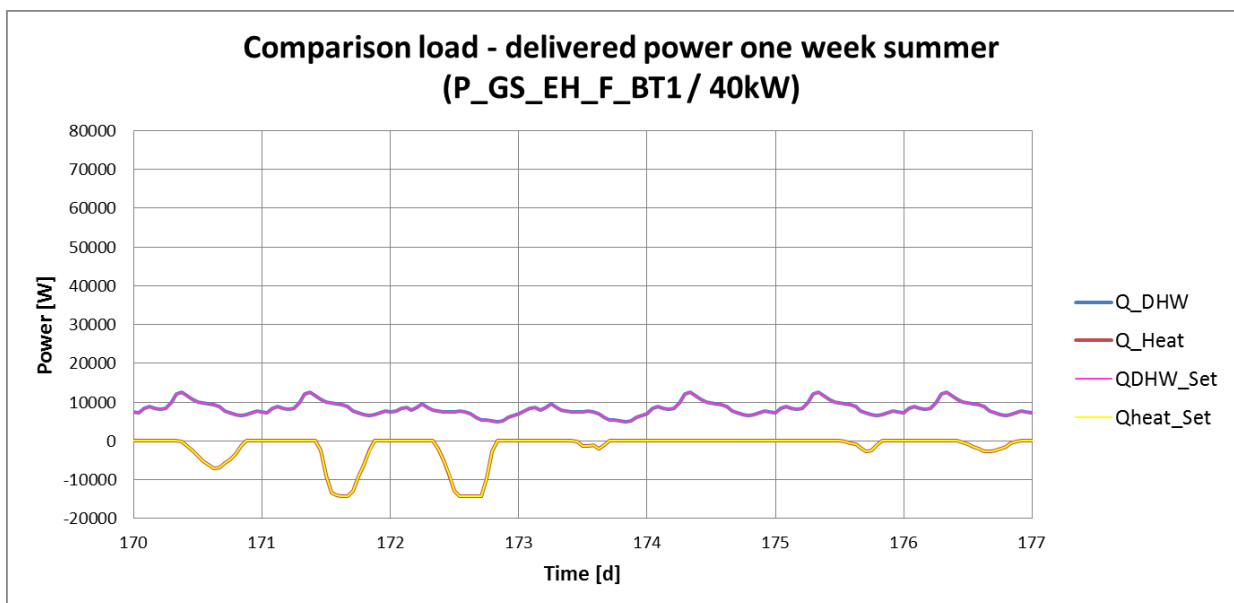
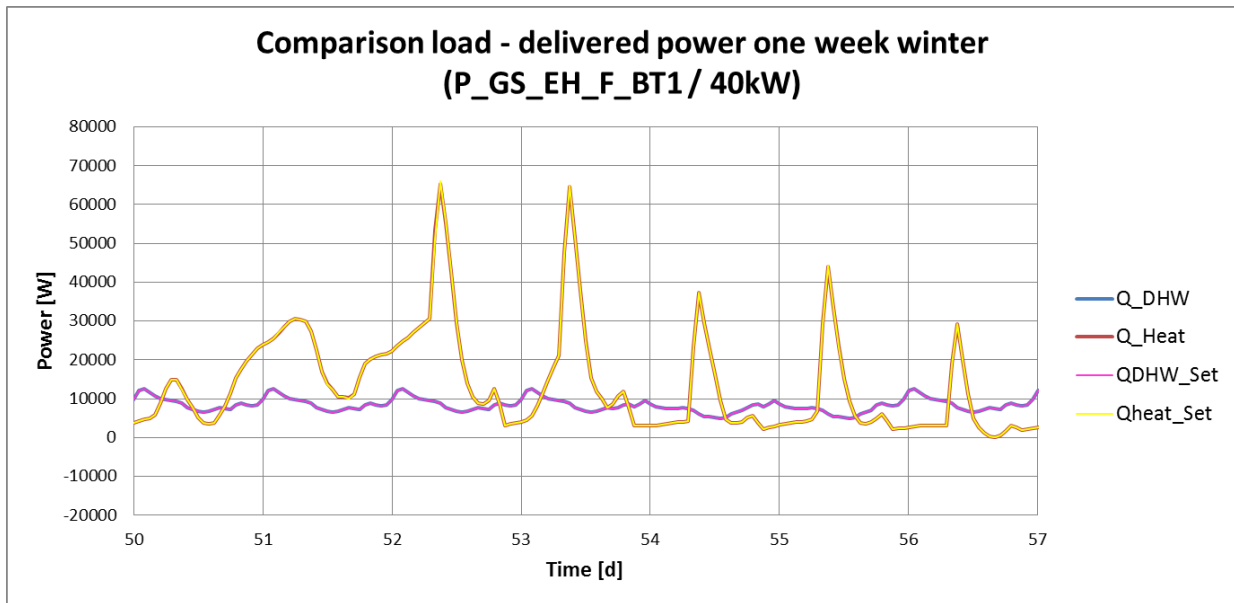




A4. Weekly plots

This appendix includes weekly plots which are referenced in the discussions. The plots are summarized here to keep the report readable. Nevertheless there are some interesting facts to see in those figures. Always at the top of the plots the section they belong to is referenced.

Section 4.1.2 Delivered power



Section 4.1.4 Heat pump

