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Modelling and Analysis of Heat Pumps for Zero Emission Buildings

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Master of Energy Use and Energy Planning
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MASTER THESIS

for

Leif Småland

Spring 2013

Modelling and Analysis of Heat Pumps for Zero Emission Buildings

Modellering og analyse av varmepumper for nullutslipps-bygninger

Background and objective

There is a considerable national and international activity regarding the development, planning and construction of the next generation high-efficiency buildings, denoted passive houses, zero-energy buildings and energy-plus buildings. At the research centre at NTNU-SINTEF, "Zero Emission Buildings" (ZEB) the main goal is to develop products and concepts for existing and new residential and non-residential buildings, which will lead to a breakthrough for zero emission buildings with regard to construction, lifetime operation and demolition/disposal. A part of the research activity addresses high-efficiency heating, cooling and ventilations system including combined heat pump and cooling systems. Development of methodology and simulation tools for modelling of these systems is important in order to design, evaluate and optimize the overall performance of the installations at an early design stage.

The Master thesis consists shall comprise the development of a software/tool for the design of heat pump systems heating and cooling of non-residential ZEB. This includes the implementation of a Beta-version of the design tool and its preliminary evaluation using realistic test cases. In practice, the project work already performed by the student was a preparation work to define the relevant parameters for the design process and the corresponding software algorithm.

This Master thesis is linked to the activities of the Norwegian ZEB centre at NTNU-SINTEF as well as the IEA Heat Pump Programme Annex 40, "Heat Pump Concepts for Net Zero Energy Buildings".

The following tasks are to be considered:

1. Develop and implement a Beta-version (i.e. proof of concept) of the early-stage decision making software. The project report was mainly devoted to define the quantitative and qualitative criteria that should be included in this decision process, and the student has successfully established a corresponding algorithm defining the software structure. The objective in the Master thesis is thus to implement this algorithm in a suitable programming language (e.g. Mathlab).

2. Define the default values for the mandatory input parameters. As some model parameters may be missing during an early-phase design, it has been decided that the software tool should be equipped with default values to support calculations. The student should collect these default values for the mandatory input parameters (i.e. those that cannot be excluded in the design procedure). As this task could be highly time consuming, the student will have to find a good trade-off between the accuracy and the resources to establish these default values in a reasonable period of time.

3. Demonstrate the early-stage decision making tool for heat pumps in ZEB. A consistent test case of a passive office building should be used in order to test and illustrate the developed software. As the main assumption motivating this work was that the design of heat pumps in the context of ZEB could be different than with standard buildings, this test case can be used to check this basis assumption. For example, the following effects can be investigated:

    a. Influence of the ratio between the base and peak loads in ZEB (compared to standard buildings).

    b. Influence of the peak load system selection in the context of ZEB buildings (compared to standard buildings).

    This analysis should be followed by a sensitivity analysis, i.e. a robustness analysis of the optimum ZEB concept with regard to uncertainties in the input parameters.

4. The work will be concluded by a discussion on results and limitations as well as by recommendations for potential future developments.

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

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

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

The candidate is requested to initiate and keep close contact with his/her academic supervisor(s) throughout the working period. The candidate must follow the rules and regulations of NTNU as well as passive directions given by the Department of Energy and Process Engineering.

Risk assessment of the candidate's work shall be carried out according to the department's procedures. The risk assessment must be documented and included as part of the final report. Events related to the candidate's work adversely affecting the health, safety or security, must be documented and included as part of the final report. If the documentation on risk assessment represents a large number of pages, the full version is to be submitted electronically to the supervisor and an excerpt is included in the report.

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

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

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

Department of Energy and Process Engineering, 14th January 2013

Olav Bolland
Department Head

Jørn Stene
Academic Supervisor

Research Advisor: Laurent Georges, NTNU

PREAMBLE

This thesis is the written final work of my Master's degree at the program of study "Energibruk og energiplanlegging" at the Department of "Energy and Process Engineering" at "the Norwegian University of Science and Technology" (NTNU). The work has been carried out in the spring semester of 2013, and is a continuation of the work of a project report written the fall semester of 2012.

The thesis is written as a supplement to a Beta-version simulation tool for early stage decision making of energy supply strategy. It can find the best strategy for any given building, including Zero Emission Buildings. The work is performed as part of the Zero Emission Building (ZEB) Centers efforts to create a full scale decision making simulation help tool, for determination of energy supply strategy for any given building.

The first half of the semester was used to obtain the necessary programming skills in the programing-language of Matlab were it at an early stage became apparent that the original scope had to be reduced. The thesis was written in the second half of the semester.

Associate professor, at NTNUs "Department of Energy and Process Engineering", Jørn Stene has been the official supervisor, and has given advice to the development and content of the thesis. He has always been available and ready to help. Co-supervisor, postdoctoral researcher at NTNUs "Department of Energy and Process Engineering", Laurent Georges has also given advice to the development and content of the thesis and the programming of the simulation tool. His office has always been open as a meeting point for discussion regarding the thesis matter. Both their help and guidance have been utmost welcome and is greatly appreciated. Kjell Kolsaker should also be mentioned and thanked for his contributions and help with the programming of the simulation tool. Gratitude to other contributors at NTNU and from the HVAC industry is also given.

And finally a great appreciation is shown to my life partner, Christine Scheie Danielsson for her supporting being and actions. The work of the Master program would have had many more practical hurdles if it was not for her.

Hopefully the work and results of this thesis will contribute to the development of a full scale simulation tool for early stage decision making regarding energy supply strategy for Zero Emission Buildings.

Trondheim June 2013, Leif Småland

SUMMARY

The work of this Master thesis is a continuation of a project work. This defines qualitative and quantitative parameters needed to make a simulation tool for early-stage decision making with regards to the energy supply strategy for non-residential Zero Emission Building (ZEB). The work is based on the assumption that the heat pump (HP) technology will be one of the core technologies for the energy supply strategy in the ZEB concept. The simulation tool proposed should be able to find the best energy supply strategy for the building, and its design parameters. It is believed that the design parameters for the energy supply strategy are different for ZEB than for standard building concepts, both when it comes to the optimal HP power coverage factor and preferred energy supply strategy (combination of technologies).

In this Master thesis, the algorithm and methodology behind a Beta-version simulation tool, similar to that proposed in the project report, is presented. The recommended energy supply strategy is determined based on technical-economic considerations. The explanation of the algorithm and methodology is followed by a proof of concept, where the simulation tool is tested on a benchmark office building. This is to check whether ZEBs have different design characteristics compared to other building concepts. As the simulation tool also can be used on different building standards, e.g. TEK10 and passive buildings, this can be verified.

Through the first part of the thesis, the algorithm and methodology used to obtain the design characteristics for the energy supply system are presented. Various delimitations and simplifications are made, some being different than the concept proposed in the project report. The input parameters needed to perform the calculations are somewhat inaccurate, as the time to acquire them was limited. The original scope of the simulation tool presented in the project report would be to comprehensive for the Master thesis.

Further, the benchmark building is presented and simulations on a TEK10, passive and ZEB are performed. To see if the simulation tool gives valid results, the outputs found for the TEK10 building are tested against some pre-defined expected range of results. These are reached, so that it is believed that the Beta-version simulation tool gives plausible output. Generally the energy supply strategies with low capital costs perform best, which are also the most CO_2-emission intensive solutions.

The findings for the passive office version of the benchmark building are also likely to be valid. Lower annual costs for the energy supply systems are found and particularly the operational costs, which are expected for a building with a more energy efficient envelope. It is also found that a lower HP power coverage factor is required to obtain large energy coverage, and its physical interpretation is given.

The ZEB building must counterbalance all CO_2-emissions associated for operation of (here) the HVAC and domestic hot water (DHW) systems. As expected, for the ZEB office, the energy supply strategy design parameters have changed drastically. The cost optimal energy supply for the TEK10 and the passive office were relatively CO_2-intensive, which is disadvantageous if these emissions would have to be counterbalanced. In general, the less CO_2-intensive systems are the preferred ones to reach the ZEB balance. While for the more CO_2-intensive alternatives, the optimum HP power coverage factor has gone up leading to higher energy coverage and thus less CO_2-emissions.

The results found in this thesis have a large degree of uncertainty. Their tendency should therefore only be seen as indications. However, also through a sensitivity analysis of the output, the simulation tool proves to perform as wanted and to give plausible results. The output is therefore considered as an acceptable proof of concept of the algorithm and methodology which could be used in a more advanced version of the simulation tool. To have a well-functioning full scale version, the simplifications implemented in the algorithm should be checked and the system solutions included should be analyzed and evaluated before implementation.

SUMMARY (NORWEGIAN)

Arbeidet i denne Masteroppgaven er en videreføring av arbeidet i en prosjektrapport. Der ble det gjort rede for kvalitative og kvantitative parametre som må fremskaffes for å lage et simuleringsverktøy for beslutningstakning med hensyn til energiforsyningsstrategi for "Zero Emission Building" (ZEB) yrkesbygg. Arbeidet er basert på antagelsen om at varmepumpeteknologi (VP-teknologi) vil være en av de viktigste teknologiene for energiforsyning til ZEB-konseptet. Det foreslåtte simuleringsverktøyet bør være i stand til å finne den beste energiforsyningsstrategien for bygningen, og dets egenskaper. Det er finnes indikasjoner på at designparametrene for energiforsyningsstrategien er ulik for ZEB samenlignet med andre bygningsstandarder, både når det gjelder optimal VP-effektdekning og foretrukket energiforsyningsstrategi.

I denne Masteroppgaven er algoritmen og metodikken bak en Beta-versjon av et simuleringsverktøy presentert, lignende det som er foreslått i prosjektrapporten. Den anbefalte energiforsyningsløsningen er gitt på bakgrunn av en teknisk-økonomisk betrakning. Forklaringen av algoritme og metodikk etterfølges av et konseptbevis, hvor simuleringsverktøyet er testet på et referansekontorbygg. Dette er for å sjekke påstanden om at ZEB har ulike designparametre samenlignet med andre bygningskonsepter. Ettersom simuleringsverktøyet også kan brukes på andre bygningsstandarder, for eksempel TEK10 og passiv-bygninger, kan dette bekreftes eller avkreftes.

Gjennom den første delen av avhandlingen presenteres algoritmen og metodikken som er benyttet for å finne de ønskede resultatene om sytstemegenskapene. Ulike avgrensninger og forenklinger er gjort, flere enn det som er foreslått i prosjektrapporten. De ulike parametrene som trengs for å utføre beregningene er noe unøyaktige, ettersom innsamling av dette ellers ville vært svært tidkrevende. Simuleringsverktøyets opprinnelige omfang, slik det er presentert i prosjektrapporten, er derfor redusert da det ville vært for omfattende for Masteroppgaven.

Videre er referansebygget presentert og det er utført simuleringer på en TEK10-, er passiv- og ZEB-versjon av bygget. For å se om simuleringsverktøyet gir sannsynlige resultater, er dataene fra TEK10-bygningen testet mot noen forventede og forhåndsbestemte data. Dataene stemmer bra, og det er antatt at simuleringsverktøyet gir fornuftige resultater. Generelt sett gjør energiforsyningstrategiene med lav investeringskostnad det best, men disse er også løsningene som er mest CO_2-utslippsintensive.

Resultatene for passiv-versjonen av referansebygget virker også å være sannsynlige. Det er funnet at årskostnadene generelt er lavere for energiforsyningssystemene, og da spesielt

driftskostnadene. Dette er som forventet for en bygning med en mer energieffektiv bygningskropp. Det er også funnet at lavere VP effektdekningsgrad er nødvendig for å fortsatt oppnå høy energidekning, og det er vist hvorfor dette er sansynlig. De andre resultatene er ganske lik de som finnes for TEK10 bygningen.

Da Zero Emission Buildings må utbalansere alle CO_2-utslipp assosierert med drift av (her) VVS-anlegget og for at produksjon av varmtvann for referansekontoret, er forutsetningnene for valg av energiforsyningsstrategi anderledes. Som indikert på forhånd har energiforsyningsstrategiegenskapene endret seg drastisk for ZEB-kontoret. De foretrukne energiforsyningsstrategiene for TEK10- og passiv-kontoret er forholdsvis CO_2-intensive, noe som uheldig når utbalansering tas hensyn til. Generelt er de mindre CO_2-intensive systemløsningene foretrukket for ZEB, mens de mer CO_2-intensive alternativene har fått høyere optimal VP effektdekning, og dermed høyere energidekning, for å redusere CO_2-utslippene.

Resultatene som er funnet i denne avhandlingen har en høy grad av usikkerhet, og tendensen i resultetene bør derfor bare ses på som indikasjoner. Imidlertid er resultatene som er funnet for simuleringsverktøyet, også gjennom en følsomhetsanalyse, som ønsket og gir sansynlige resultater. Dataene er derfor ansett som akseptable som et konseptbevis for en lignende fullversjon av simuleringsverktøyet. For å få en velfungerende fullskalaversjon, bør forenklingene implementert i algoritmen bli evaluert og systemløsningene som er, og skal bli, implemntert bør analyseres og evalueres.

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NOMENCLATURE

Abbreviations:

ASHP	= Air Source Heat Pump
CO2	= Carbon Dioxide
COP	= Coefficient of Performance
DHW	= Domestic Hot Water
DOT	= Dimensioning Outdoor Temperature
EN/CEN	= Comité Européen de Normalisation
GSHP	= Ground Source Heat Pump
HVAC	= Heating, Ventilation and Air Conditioning
HP	= Heat Pump
ISO	= International Organization for Standardization
LMTD	= Logarithmic Mean Temperature Difference
NG	= Natural gas
NS	= Norwegian Standard
PV	= Photovoltaic (panels)
SPF	= Seasonal Performance Factor
TYM	= Typical Metrological Year
ZEB	= Zero Emission Building

Symbols:

$\dot{\mathbf{Q}}$	= Thermal energy flow rate (kW)
$\mathbf{Q}$	= Thermal energy (kWh)
$\dot{\mathbf{m}}$	= Mass flow rate (kg/s)
$\mathbf{c_p}$	= Specific heating capacity (kJ/kg)
$\mathbf{\Delta t}$	= Temperature difference (°C)
$\mathbf{A}$	= Area (m^2)
$\mathbf{U}$	= U-value (W/m^2K)
LMTD	= Logarithmic Mean Temperature Difference (K)
$\dot{\mathbf{W}}$	= Electric power (kW)
P	= Power (kW)
kWp	= kilo watt peak (one kW production under standard test conditions for PV)

Terms:

Airborne energy distribution	: When air is used to transport thermal energy (hot or cold air).
Energy supply strategy	: Combination of heat pump technology, peak power system, emission and distributions system for heating and cooling.
Free cooling	: Cooling by directly dumping heat to an environmental sink.

1. INTRODUCTION

Of the worldwide human energy use, the building sector is estimated to consume about 40%. Greenhouse gas (GHG) emissions associated to the same sector represent 24 % of the global total (Ayoub, 2008). With increasing focus on reducing energy use and minimizing climate change, it is more and more crucial to build sustainable. Keeping in mind that today's buildings are going to be here for a long time, it is important to build for the future. The Zero Emission Building (ZEB) is a building concept as a result of these conditions.

There are several ways to influence the rate of GHG-emissions during operation of a building, and the most obvious solutions are to improve the building envelope and/or to use energy sources and systems associated with low CO_2-emissions. The International Energy Agency (IEA) have formed a Heat Pump Programme in which they recommend the use of heat pumps (HP) and HP related technologies in all applications where it can reduce energy use for the benefit of the environment. Heat Pump Programme Annex 40, "Heat Pumps for Zero-Energy Buildings" is of the latest projects, and is part of the foundations behind the presented work (Center, 1974). No conclusions are made so far, as start-up of the Annex has just begun, but there are strong indications that there will be a recommendation for use of HP as one of the core technologies in the ZEB concept. HP can provide both heating and cooling with low primary energy input, and is therefore a suitable technology for ZEB.

This Master thesis is a continuation of a project report submitted in the fall semester of 2012. In the project report, relevant parameters needed to conduct an early stage selection/recommendation of energy supply strategy for a building in general and Zero Emission Building in particular were defined. An algorithm for a simulation tool analysing all possible energy supply strategy combinations was suggested in the report.

The algorithm presented in the project report is taken into use for this Master assignment. A Beta-version simulation tool for early stage decision making of energy supply strategy in buildings and ZEB, with HP as core technology, is programmed in Matlab prior to the writing of this thesis. In the project report, some output criteria are suggested, and these are used as basis in the development of the simulation tool (Table 1).

Table 1 - The output parameters from the simulation tool used as decision criteria.

- **Heat source/sink for the HP**
- **Thermal energy emission strategy**
- **Peak load and/or backup technology**
- **HP power coverage factor (modified compared to the project report)**
- **Energy coverage factor of the HP**
- **Estimated of CO_2 emission and total, operational and annual capital costs (changed compared to the project report)**
- **Required installation of PV panels (modified compared to the project report)**

The Master thesis is written on the assumption that the reader know the basic principles of heat pumps and how cooling techniques and conventional heating systems work. The reader is also expected to have basic knowledge about distribution systems for heating and cooling, energy emission technologies and operation strategies for buildings. It is also an advantage to be familiar with "common" terms from the HVAC-community/industry.

1.1 METHOD

In the development of the Beta-version simulation tool, resource personal from the Faculty has mainly been used to acquire the required knowledge to perform the programming, but also the support pages of MathWorks (Matlab developers) has frequently been visited.

The required default values needed in the simulations have been acquired by literature search and by help from supervisors. However, the trade-off between accuracy and resources to establish them influences their credibility, but they should be sufficient for the purpose of illustrating the concept of the simulation tool.

For the demonstration of the Beta-version simulation, output according to Table 1 are analysed and commented. The benchmark building used for the demonstration of the Beta-version simulation tool is a thoroughly prepared office building model developed and previously used in another Master thesis, "Analysis of Simplified Hydronic Heat Distribution System for Non-Residential Buildings, 2012". A TEK10 and a passive house version of the benchmark building are used in the simulations.

1.2 THESIS STRUCTURE

Chapter 2: The first part of the thesis is devoted to explanation of the algorithm and methodology behind the Beta-version simulation tool.

Chapter 3: The Beta-version software tool will be used to demonstrate the effect of building standard with regard to optimum energy supply strategy and HP power coverage factor. A sensitivity of the results, by some important parameters, is used to check the robustness of the results and calculation methodology. Lastly, a Section to illustrate the use of night setback is presented.

Chapter 4-5: The final Chapters of the thesis are devoted to conclusions on the results and proposals for future work.

The Beta-version simulation tool is a proof of concept whether or not a simulation tool for early stage decision making regarding the energy supply strategy can be made? Some criteria should therefore be met:

- It should be able to give output data according to the parameters in Table 1 and rank the energy supply strategies by annual costs.
- It should also be possible to alternatively select energy supply strategy based on CO_2-emissions.

The presented work will hopefully contribute to the knowledge in the development of ZEB early-stage decision making tools devoted to the selection of energy supply strategy.

2. THE SIMULATION TOOL

In the preliminary work with the project report, qualitative and quantitative parameters needed to make a simulation tool were discussed. On that basis a Beta-version simulation tool has been developed for early-stage decision making regarding the energy supply strategy of a ZEB.

The history behind the ZEB concept is explained in the project report. There is yet no official definition for the Zero Energy/Emission Building concept and the system boundaries are a hot topic. However, a definition of the understanding of ZEB for the work of the project report was given. The basis of this definition is adopted and also used in this Master thesis. In this context a Zero Emission Building is understood as: "A non-residential building where CO_2-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, 2012). Energy for appliances and materials is not included.

The simulation tool is developed so that is works for all non- residential buildings; and for ZEB, installations for counterbalancing CO_2-emissions are included in the calculations. The simulation tool calculates the annual cost related to a given energy supply strategy based on operational and capital costs. As the HP technology is expected to be a core technology in the ZEB concept (ref., "Introduction"), the simulation tool focuses on this. The simulation tool will for any given HP power coverage factor be able to calculate the annual cost for each energy supply strategy. The energy supply strategy with the lowest annual cost is the recommended one. Figure 1 illustrates how the optimum HP power coverage factor is found as function of the total cost, which is the sum of operational and capital costs.

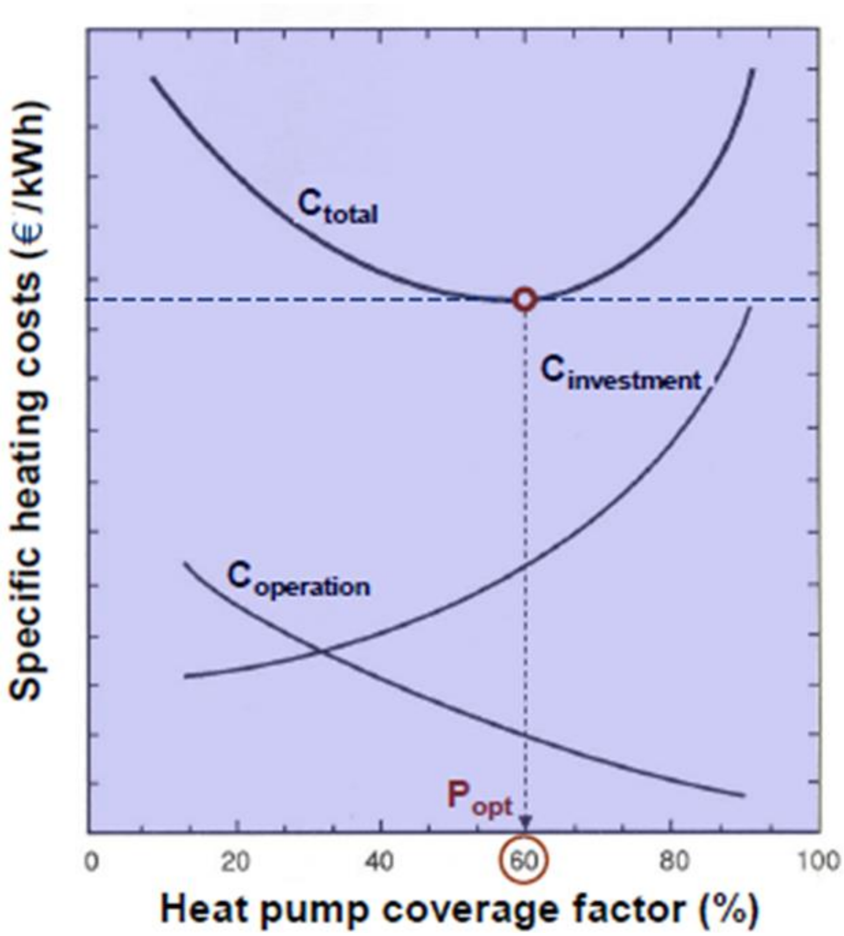


Figure 1 – Illustration of total cost (sum of operational and capital cost) of an energy supply strategy can change with HP power coverage factor: the optimum power coverage factor is given by the lowest total annual cost (Stene, 2012)

Operational costs are depending on:

- Energy cost for operation of the HP and peak power system.
- Electricity cost for pumps and fans.
- Maintenance cost of the equipment.

Annual costs for the investments are determined on the initial capital cost times the annuity factor (a) of the investments involved.

The simulation tool is able to compare the annual costs at the optimum design point for all possible combinations of all subsystems in the energy supply strategy. The system with the lowest annual costs is the recommended one. If the maximum cooling requirement is higher than the optimum power coverage factor in heating mode for the HP, the cooling power is overriding the design point of the HP system. This is because the HP must be able to cover the entire cooling demand.

2.1 WHY A SIMULATION TOOL?

For energy supply strategies meeting the indoor comfort criteria, the one with the lowest annual cost is usually selected. The simulation tool is programmed on this basis.

For "normal" buildings (e.g. TEK10), there are some "rules of thumb" that are often applied in the selection of energy supply strategy and HP power coverage factor. They are used frequently by the consultant business. However, there are indications that the same rules does *not* apply for ZEB. The software tool will be used to verify whether this is the case or not. Some of these "rules of thumb" are listed here:

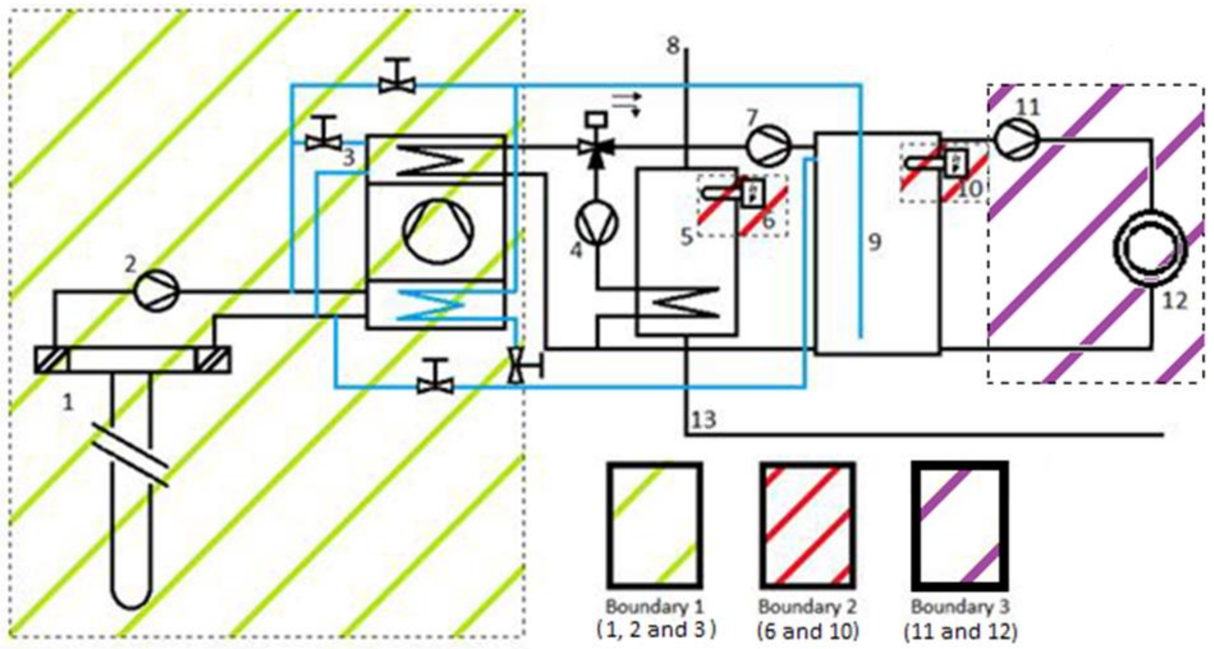
- About 40-70 % HP power coverage factor gives 70-90 % energy coverage for air source heat pumps (ASHP) in different climate zones in Norway.
- Use a "cheap" peak power system in combination with HP base load.
- The total annual cost curve (ref. Figure 1) is relative "wide" and symmetric near the optimum.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

The rules are quite the same for passive buildings, but they are similar. Lower power coverage should still give high energy coverage for passive buildings, other than that the results are expected to be more or less the same.

In practice, the main factor that distinguishes ZEB from passive houses/buildings is the need for on-site energy producing equipment to counterbalance the CO_2-emissions associated to the buildings operation. As this has an impact on the total capital cost of the building, and thus the annual costs, it should be investigated if there are considerable differences in design features between the building standards. ZEB is affected by operational energy use in two ways ("normal" operational costs *and* annual payback for the capital cost of the energy producing equipment to counterbalance the CO_2-emissions associated to operational energy use). It should therefore in theory be more sensitive to the emission rate of the energy source used for operation of the building. The simulation tool is needed to check if these assumptions are correct.

2.2 THE SIMULATION BOUNDARIES

It is found appropriate to have three boundaries for the energy supply strategy; (1) the HP and heat source/sink, (2) peak power/backup system and (3) distribution and emission system. The three boundaries are shown in Figure 2.



Key

1	heat source/sink system (here: vertical boreholce heat exchanger)	8	DHW hot water outlet
2	source/sink pump	9	buffer storage
3	heat pump	10	space heating back-up heater
4	DHW storage loading pump	11	circulation pump space heating distribution subsystem
5	DHW storage	12	energy emission subsystem
6	DHW back-up heater	13	DHW cold water inlet
7	primary pump		

Figure 2 - System boundaries of the simulated energy supply strategies.

Boundary 1 (green diagonals) marks the HP and heat source/sink. Operational costs in this boundary include energy to operate the system in heating, cooling and/or free cooling mode (key 2 and 3), as well as maintenance costs. Capital costs are associated to the heat source/sink and HP unit costs (key 1, 2 and 3), which are given by the size of the installation.

Boundary 2 (red diagonals) marks the peak power/backup heating system (key 6 and 10). Capital cost is linked to the design heat load of the heating system, and the operational costs are linked to the heating energy covered by peak the load.

Boundary 3 (purple diagonals) marks the thermal energy emission system and the related distribution system (key 11 and 12). Dependent on emission strategy, the investment and installation cost will vary. Operation cost will mainly be due to the operation of the distribution pumps and system.

The keys not marked by the boundaries; buffer tanks, piping and other “support systems” (key 4, 5, 7 and 9), are excluded from the calculations in the Beta-version simulation tool. It is assumed, as a first approximation, that the related costs are constant between the different strategies investigated here. As proposed in the project report, the hot water production is optimized in a separate optimization loop (Småland, 2012). This is elaborated in Section 2.3.12, “Domestic hot water”.

The three boundaries in Figure 2 are seen as puzzles that can be replaced by other subsystems with the same function. Within the boundaries, changes will affect the other parts of that subsystem, but if the entire subsystem is replaced it will not affect the function of the other boundaries or itself. However, if a piece of the puzzle is changed, it can/will change the operational cost of the entire energy supply strategy system, as well as influence the (more obvious) capital cost. The simulations tool is able to find the annual total cost for any defined energy supply strategy and HP power coverage factor. The annual cost is given for the system from one to one hundred percent HP power coverage factor, as illustrated in Figure 1. The HP power coverage factor where the annual total cost is lowest will be the recommended design point for the HP (unless the cooling requirement calls for higher power).

For ZEB, the cost associated with the energy generating equipment, that counterbalances the CO_2-emissions associated to the energy use of the energy supply system, must be found. By having an additional calculation procedure that adds the annual investment and maintenance cost of the equipment to that of the energy supply strategy, this is found. This will most likely change the annual investment and operational curve to such a degree that the optimum HP power coverage factor is shifted significantly (ref. Figure 1).

2.3 THE PROGRAMMING

To have a workable simulation tool within the timeframe of a Master thesis, some simplifications and delimitations have been made. The following Sections address the simplifications and delimitation in the Beta-version simulation tool. Also what should/could be done in a final version of the simulation tool is proposed.

2.3.1 WHAT IS INCLUDED IN THE BETA-VERSION SIMULATION TOOL

In the original concept given in the project report, a comprehensive range of system solutions were proposed. However, delimitations are made here. The three different boundaries forming the energy supply strategy have a limited amount of “available” technologies in the Beta-version simulation tool, which is also the case for CO_2-emissions counterbalancing technologies (for ZEB). The energy supply strategy systems included in the Beta-version simulation tool are listed in Table 2.

Table 2 - A list of the different subsystems that are included in the Beta-version simulation tool that together can form an energy supply strategy.

Boundary 1	Boundary 2	Boundary 3
Air source heat pump (ASHP)	Electric boiler (el.)	High[1] temperature radiators (here 60/50 ºC) and beams for cooling (here 10/15 ºC)
Ground source heat pump (GSHP)	Bio-boiler (bio)	Low temperature radiators (here 50/40 ºC) and beams for cooling (10/15 ºC)
	Natural gas boiler (NG)	Floor heating (here 35/30 ºC) and floor cooling system (here 16/19 ºC)
As power generating, CO_2-emissions counterbalancing, equipment only photovoltaic (PV) panel is included.		

The solutions included in the Beta-version altogether form 18 different combinations. In the Beta-version simulation tool the radiator systems are always in combination with cooling beams and the floor heating system is always in combination with floor cooling. As CO_2-emissions counterbalancing technology, PV is considered the most relevant for this thesis as it can produce electricity in the largest range of locations, and without side-effects like flue gases, noise or possible overproduction of heat. These delimitations should be sufficient to prove the concept of different optimum heat pump coverage factors and energy supply strategies for the different building standards.

2.3.2 THE INPUT DATA

There are many factors affecting the performance of the energy supply strategy, and a significant number of inputs are needed for it to work. The inputs can be divided into three categories:

- Building simulation output without HVAC limitations (here called: “the SIMIEN-file)
- Building specific input
- Default input

The SIMIEN-file is output data from an “Annual simulation” file form (an energy and indoor climate program) SIMEN, built on the dynamic calculation method described in NS3031 (ProgramByggerne). This file contains one hour resolution values for; power use (heating and cooling), outdoor and indoor temperatures over a typical metrological year (TMY) for a given location. There are some advantages to the fact that the outputs from this file are given in hourly time steps. First of all it provides relatively good resolution for the calculations, and secondly it makes calculations somewhat easier, as heating power of X kW for one hour also gives X kWh, in energy use. This reduces the risk of miscalculations and is

[1] High for HP, but not in common sense. 80/60 and 70/50 would normally be considered high temperature.

therefore beneficial. SIMIEN is not the only program on the market that could be used, but the Beta-version simulation tool is built around the output from this particular program.

The building specific values are given for the specific simulated building with its particular orientation and location. These values will change from building to building and location to location. The list of parameters needed in the calculations is given here:

- Room heating and cooling power requirement at design conditions
- Ventilation heating and cooling power requirement at design conditions
- Annual energy use for domestic hot water
- Building size (heated floor area)
- Energy recovery unit efficiency (average value)

The data in the list are (all) available in the project phase where a SIMIEN-file has been made for the building envelope design. The design condition parameters can be found by using the SIMIEN-function “Winter simulation” and “Summer simulation”. There are, however, some issues using the built-in design condition functions in SIMIEN, and if the user is not aware of this the calculation should be done manually (Smedegård, 2013). Annual energy for domestic hot water is an output from the “Annual simulation”-result file in SIMEN, but it is not available in the “Annual simulation” file, and it has to be manually inserted as an input for the simulation tool. Building size and energy recovery unit efficiency are both inputs in the SIMIEN-file, but must also be manually inserted into the simulation tool.

As stated earlier, the HP is always dimensioned so that it can cover the entire cooling requirement. In this thesis, a one to one relationship between cooling power and heating power is used. There are some indications that it is not a bad approximation for air source heat pumps (ASHP) but not so good for ground source heat pumps (GSHP), but this relationship should be further investigated both HP technologies.

The default input data are consisting of some climate dependent parameters, but mainly physical parameters that are not dependent on climate. However, they might change for other reasons. The climate dependent data are in the Beta-version set to Oslo-climate, and the other parameters use standard average values from the consulting business. As these are average values, more specific data might be available, and it should therefore be possible to change them. The default values used for this work should be quality assured in the further development of a final (version) simulation tool.

The final list of building specific and default input data are given in Appendix 1. However, to have a well-functioning (final) simulation tool, a data base of costs and technology characteristics should be made and constantly updated. This job is started through work of the project report (Løtveit, 2012).

2.3.3 THE SIMULATION ALGORITHM

The input data, described in Section 2.3.2 and shown in Appendix 1, are used to find the optimum energy supply strategy for a given building. The algorithm is shown in Figure 3.

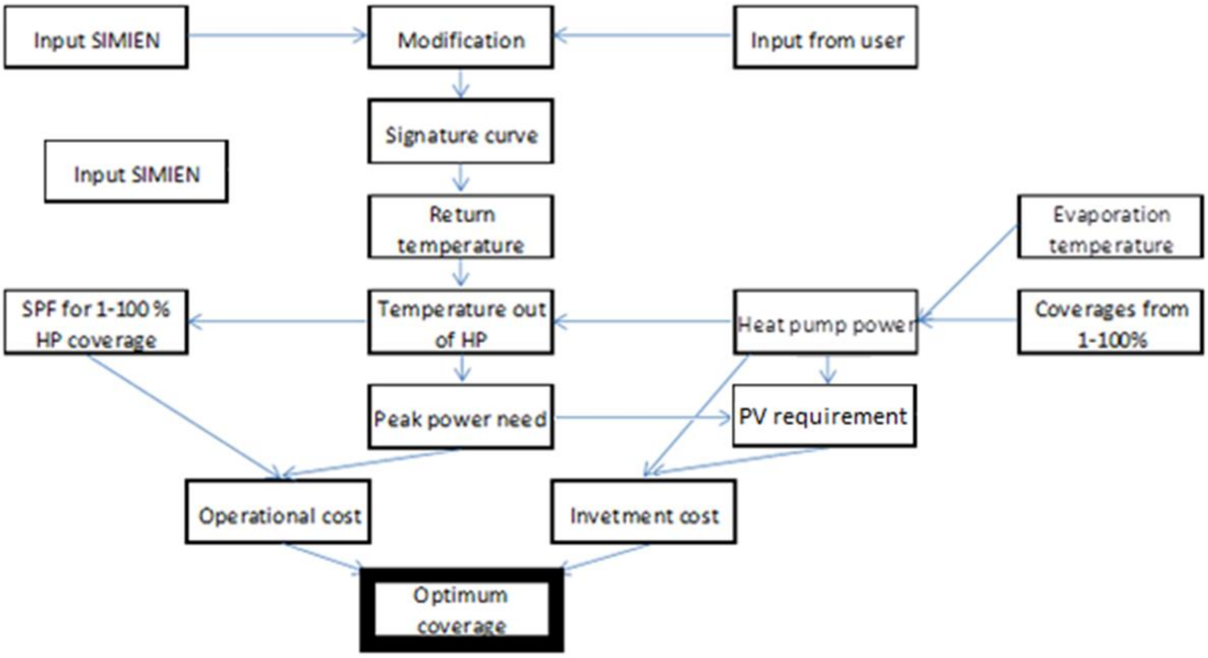


Figure 3 –The algorithm for the Beta-version simulation tool. The "Input from user"-box represents both the default values and the building specific values. Description of the algorithm is given in the thesis text, Section 2.3.3.

Figure 3 is a simplified flow chart showing the algorithm of the simulation tool. In the following bullet points, the algorithm is explained stepwise. More thorough explanations behind the actual calculations will be given in Sections 2.3.4 to 2.3.12, while the basic principles are explained here.

- Input from the SIMIEN "Annual simulation"-file, building specific user input data and the default values are modified in the simulation tool to a common unit system, ready to use in the calculations.
- Outdoor temperature compensated signature curves for both summer and winter conditions for each of the energy emission systems investigated are created, based on input for the energy emission system. As the supply temperature for the heating and cooling system (T_{set}) is given by the outdoor temperature ($T_{outdoor}$), the supply temperature is now known throughout the year.
- Further, the return temperature and flow rate in the Hydronic distribution system is calculated based on the heating and cooling power requirement of the building (i.e. ventilation and room heating).
- The available power from the HP is related to the size and temperature conditions. The evaporation temperature is fixed (based on $T_{outdoor}$ for ASHP or ground temperature T_{ground}, for GSHP), while the temperature out of the HP (T_{out}) is linked to its available power. This is calculated stepwise based on power coverage factor (1-100 percent). As a less powerful HP will have less capacity to heat the water, the outlet temperature and the COP will differentiate depending on the size of the HP (power coverage factor). This is taken into account.

- The seasonal performance factor (SPF) of the HP is calculated according to the "bin method" explained in EN 15316-4-2:2008. The bin size is 1:8760 (one bin per hour of the year).
- The HP can only provide a certain temperature lift with its available power. The remaining temperature lift that the HP cannot provide (to reach T_{set}), gives the peak power demand (volume flow times T_{out} to T_{set}). The peak power system is designed so it can cover the entire heat load, in order to also function as a backup system if the HP fails. This is not always what is done in practice, but how it is considered in the simulation tool.
- All the input energy to operate the thermal energy supply system is found as explained above. By multiplying the respective energy use by an emission rate, the CO_2-emissions to be counterbalanced by the PV panels is found.
- Now the annual operational cost can be found. It is given by the annual HP heat supply and its SPF, the energy use for the peak power system, the pump energy to distribute water in the building and to/from the heat source; as well as maintenance costs. The annual cost for the investment for the particular energy supply strategy is given by the HP power coverage factor (HP size in kW), the peak power/back-up power system, as well as the ventilation battery, the heating and cooling distribution systems, times the respective annuity factor. For a given energy supply strategy, the only varying capital cost as a function of the HP power coverage factor, is the HP and the PV.

For a given energy supply strategy (the combination of technologies/boundaries), the domestic hot water (DHW) production gives a fixed annual addition to the total costs, independent of HP coverage factor. The procedure behind the DHW cost is basically the same as for the heat emission strategy. This will be more thoroughly explained in Section 2.3.12, "Domestic hot water".

2.3.4 Data import to the simulation tool

The SIMIEN-file is not readable by Matlab as it is given. Therefore some modifications must be performed to have it usable for further calculations. By default, the SIMIEN-file will give commas as decimal separator (unless this is changed in the settings for Windows). Matlab uses dots as decimal separator, and a script where all commas are replaced by dots is made. This should also be the done in the final simulation tool.

Another modification of the SIMIEN-file is of the values of the first time steps for the room heating requirement. The heating requirement is too high; which is linked to the initialisation procedure in SIMIEN. This will give some unwanted effects to the results. Therefore the Beat-version simulation tool cancels the seven first time steps to prevent this. What should be done to this problem in the final simulation tool is something that needs to be more thoroughly analysed. Removing them however, does not add any complications, except a very small fraction of "missing energy" in the calculations.

All input data from the building specific and default values (regarding energy or power) are changed from kW or kWh to W or Wh, to have all units in the same order of magnitude and to reduce the risk of miscalculations.

2.3.5 The signature curve

The signature curve is based on two points. The first point (upper left, ref. Figure 4) is at the crossing point where the design outdoor temperature (DOT) and the design supply temperature ($T_{set,DOT}$) meets. The second point (lower right, ref. Figure 4) is at the crossing point between T_{set} at the highest or lowest (heating and cooling need respectively) outdoor temperature and that $T_{outdoor}$. In Figure 4 an example is given for a heating system.

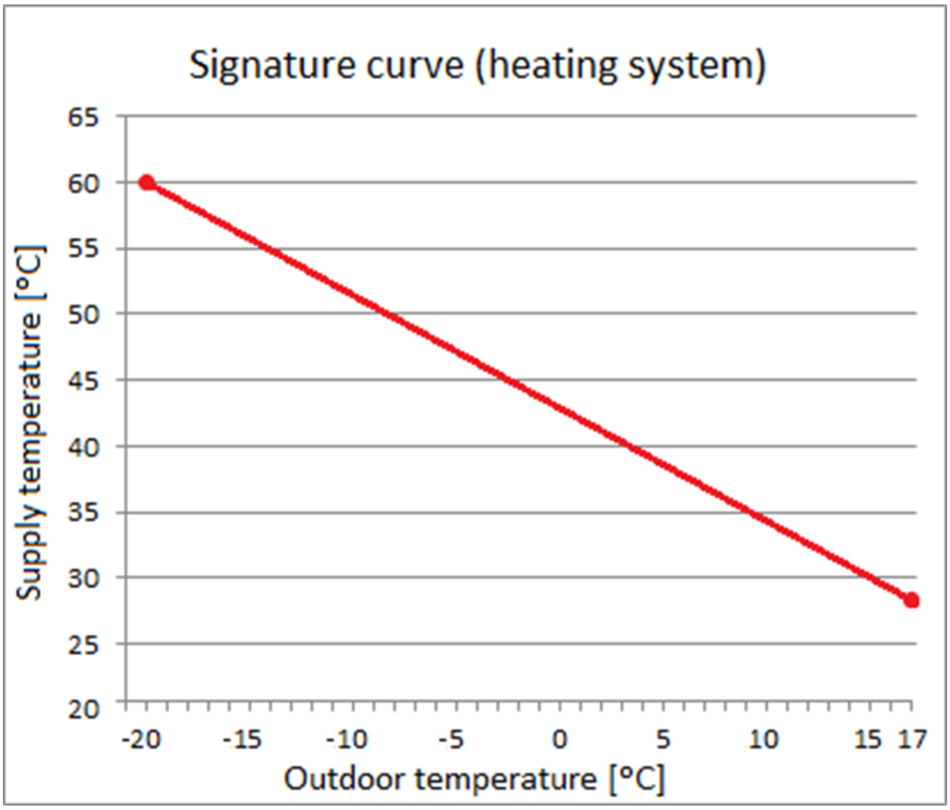


Figure 4 – Example of signature curve for a heating system: the y-axis gives the T_{set} at any given $T_{outdoor}$ (x-axis). The same principle is used for a cooling system.

There are different signature curves for the different heating/cooling emission systems. When a signature curve is available, T_{set} is always known at any given $T_{outdoor}$. For the Beta-version simulation tool, if $T_{outdoor}$ exceeds the $T_{set.DOT}$, T_{set} remains the same as for design conditions. When T_{set} is known for all $T_{outdoor}$, T_{set} is calculated for every hour of the year.

2.3.6 The return temperature

There are two return temperatures to be found:

- Return temperature from the space heating and cooling distribution systems
- Return temperature from the ventilation heating/cooling batteries

To find the return temperature of the room heating/cooling system, the power requirement of the room must be known at all times. This is available in the SIMIEN-file. First the LMTD (logarithmic mean temperature difference) between the heating/cooling emitter (e.g. radiators or cooling beams) and the operational temperature must be found, Equation 1:

$$\frac{Q}{Q_N} = \left(\frac{LMTD}{LMTD_N}\right)^n => LMTD = \sqrt[n]{\frac{Q}{Q_N}} \times LMTD_N \quad (Eq. 1)$$

$$LMTD_N = \frac{T_{sup,N} - T_{ret,N}}{log\left(\frac{T_{sup,N} - T_{indoor,N}}{T_{ret,N} - T_{indoor,N}}\right)} \quad (Eq. 1.1)$$

Table 3 - List of symbols for Eq.1 and Eq.1.1

Q = power requirement
Q_N = nominal power requirement
LMTD = logarithmic mean temperature difference between room temperature and heating/cooling emitter
$LMTD_N$ = logarithmic mean temperature difference at nominal conditions
n = heating/cooling emitter exponent[2]
$T_{sup,N}$ = supply temperature at nominal conditions
$T_{ret,N}$ = return temperature at nominal conditions
$T_{indoor,N}$ = indoor temperature at nominal conditions

Knowing the power requirement and supply temperature, the $LMTD_N$ of the heating/cooling emitter system and the emitter exponent, it is possible to find the return temperature needed to give the wanted heating/cooling capacity. The return temperature is found using a non-linear Equation, solved numerically using a Newton-Raphson iterative method. This is probably also the best approach for the final simulation tool as well.

To find the return temperature from the heating and cooling ventilation batteries, a far simpler approach has been used. To prevent too complex calculations, a fixed temperature difference of the incoming air and the outgoing return water is used. The incoming air temperature is calculated based on the ventilation heat recovery units' efficiency, using Equation 2.1[3]. And outgoing water temperature is found by adding (for heating) or subtracting (for cooling) the fixed temperature difference (Eq.2).

[2] The heating/cooling emitter exponent *n* indicates the change in power output of an emitter when the actual conditions, in terms of water temperature and room temperature, differ from design conditions, i.e., the values that were used to define an emitters' nominal heating capacity (Thi13). It will change some dependent on the energy emission units design and dimensions.

[3] The Equation is shown for heating mode. The formula is modified for cooling mode.

$$T_{ret,vent} = T_{in,batt} + \Delta T_{ret,air\ in} \quad (Eq.2)$$

$$T_{in,batt} = T_{outdoor} + (T_{indoor} - T_{outdoor}) \times \eta_{energy\ rec} \quad (Eq.2.1)$$

Table 4 - List of symbols for Eq.2 and Eq.2.1

$T_{in,batt}$ = temperature of the air entering the ventilation battery
$T_{outdoor}$ = outdoor temperature
T_{indoor} = indoor temperature
$\eta_{energy\ rec}$ = energy recovery unit efficiency
$\Delta T_{ret,air\ in}$ = fixed temperature difference between the incoming air and the return temperature[4]

The approach used in the Beta-version simulation tool may not be sufficient for the use of a final version, and should therefore be improved. This could be done in a process using the NTU method, where the efficiency of a battery can be found and T_{ret} could be found in an iterative process using the parameters in Figure 5 and the formulas in the NTU method (Hea13).

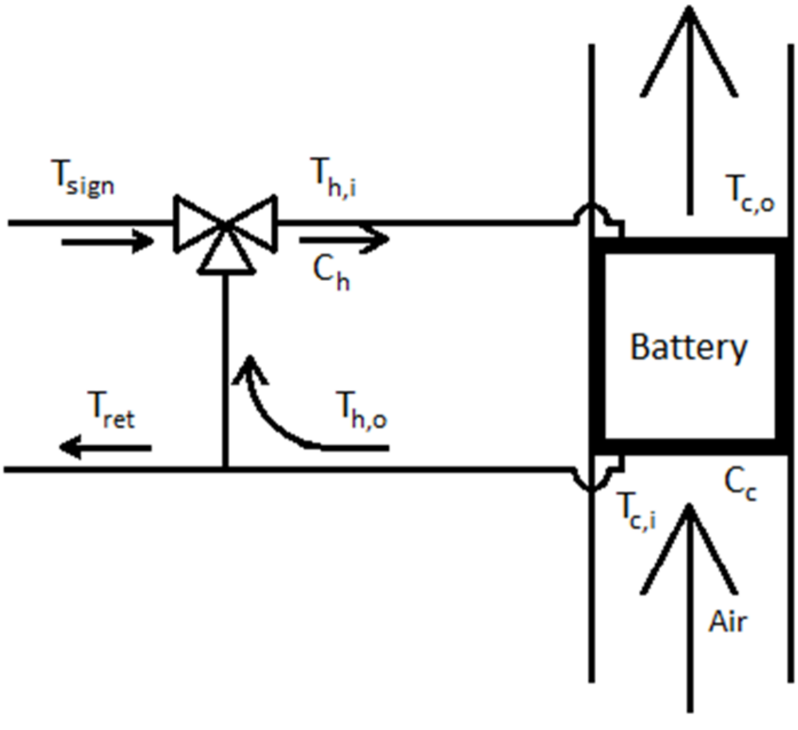


Figure 5 – An illustration of the parameters needed to find T_{ret} using the NTU method.

Figure 5 shows the most important parameters needed to find the return temperature from the battery using the NTU-method. However, there were too many uncertainties for the implementation of the method, and a trade-off between time and accuracy led to the conclusion that a simplified approach was sufficient for the Beta-version simulation tool.

[4] Not the same value for heating and cooling mode.

The mass flow of the return water for both the room and ventilation heating/cooling is found by Equation 3.

$$\dot{m} = \frac{\dot{Q}}{Cp \times \Delta T \times \rho} \quad (Eq. 3)$$

Table 5 - List of symbols for Eq.3

$\dot{m}$ = mass flow rate of water
$\dot{Q}$ = power requirement
ΔT = temp. difference between signature curve and return temp.
ρ = density of water

The combined return temperature from both room and ventilation heating/cooling is considered the return temperature going to the heating system, i.e. HP/peak power boiler. This water temperature is found by Equation 4.

$$T_{ret,tot} = \frac{\left(\dot{m}_{vent} \times T_{ret,vent}\right) + \left(\dot{m}_{room} \times T_{ret,vent}\right)}{\left(\dot{m}_{vent} + \dot{m}_{room}\right)} \quad (Eq. 4)$$

Table 6 - List of symbols for Eq.4

$\dot{m}_{vent}$ = mass flow of water from the ventilation heating/cooling system
$\dot{m}_{room}$ = mass flow of water from the room heating/cooling system
ΔT = temp. difference between signature curve and return temp.
ρ = density of water

2.3.7 HEAT PUMP ENERGY SUPPLY (HEATING AND COOLING)

The theoretical and practical performance of a HP is temperature dependent, and the return temperature mix from Equation 4 is an important parameter to find the performance of the HP. The Beta-version simulations tool has two different approaches to find the temperature out of the HP; the supply water used in the heating and cooling system. The two approaches will be explained here.

Heating mode

The HP performance should be given by the standards set in EN 14511. The temperature of the substance where energy is extracted for evaporation (brine/water/air) and outlet water temperature on the condenser side is the basis for the HP performance. As the HP will not run under test conditions during real operation, its performance at deviation from design parameters must be found. Table 7 gives the default adjustments used in the simulation tool.

Table 7 - The magnitude of change in COP and power when temperature conditions change (Stene, 2012). These are input under the "default"-category, but can be edited by the user.

Reduction of:	Change in condensation temperature (per K)	Change in evaporation temperature (per K)
COP	2.5 %	2.5 %
Power	0.5 %	3.5 %

When the T_{set} is known, the optimum temperature out of the HP will be this temperature. The inlet water temperature for the condenser is the temperature mix of the water from the room heating and the ventilation heating (ref. Eq.4). However, the HP may not have the capacity to heat the water to T_{set}. This is likely the case at high supply temperature requirements, low evaporation temperature conditions and small HP coverage factors. The actual water temperature out of the HP is therefore found using an iterative process. This principle is shown in Figure 6.

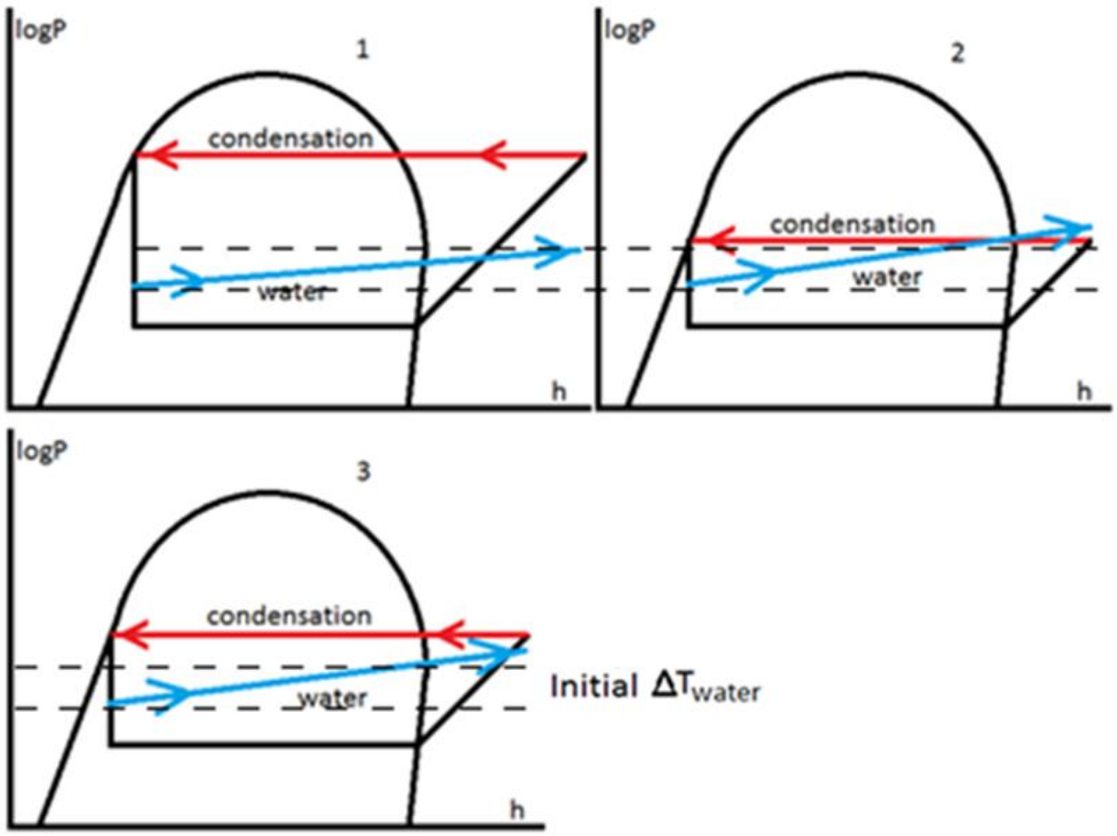


Figure 6 – Illustration of the iteration process for outgoing water temperature from the HP.

As seen in Figure 6, the condensation temperature and outgoing water temperature from the HP is iterating towards a stable state (1 to 3). High condensation temperature gives lower power, and thus low outgoing water temperature (1). The condensation temperature is moved to the previous stage outgoing water temperature, and the power increases and the outgoing water temperature increases (2). After some iterations, the condensation temperature and outgoing water temperature is stable (3 and onwards)

As stated in Section 2.3.1, “What is included in the Beta-version simulation tool”, there are two types of HP in the Beta-version simulation tool. The nominal COP is set to the same value (4.15), and it is the evaporation temperature for the HP, either related to the outdoor temperature (ASHP) or to the ground temperature (GSHP), that set them apart. For the ASHP, performance of the HP on the evaporator side is directly linked to the outdoor temperature.

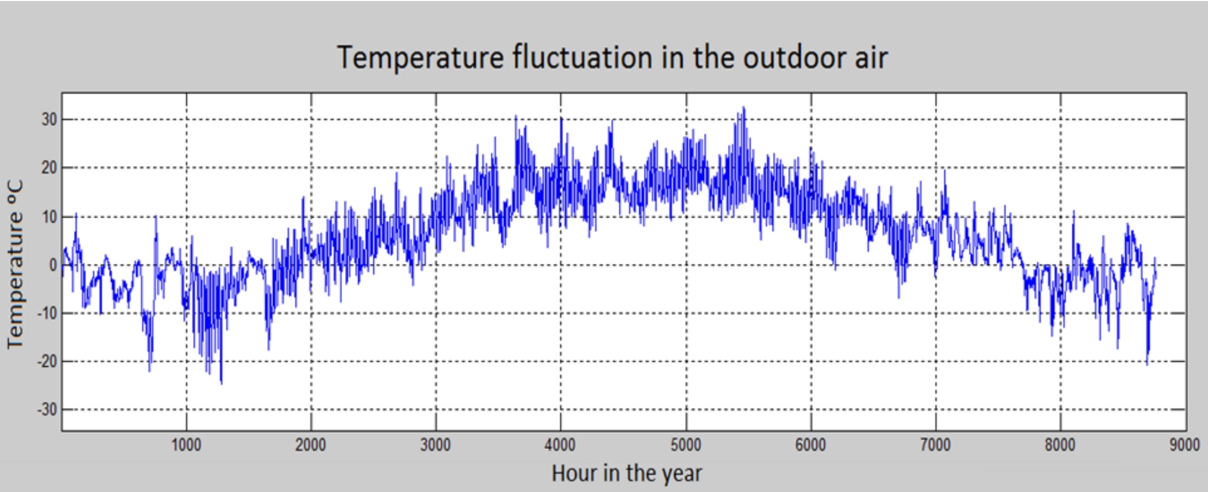


Figure 7 - Temperature fluctuations of the outdoor air for Oslo climate, as given by SIMIEN in a typical meteorological year. This is also the temperature on the evaporator side of the HP.

As seen in Figure 7, the outdoor temperature fluctuates throughout the year. The mean temperature has a sinus shape with the peak in the summer months (late July). In the Beta-version simulation tool the heat supply is only limited by the reduction in percentage (ref. Table 7). In the final version an outdoor temperature limit where the ASHP is switched off, should be introduced on both the condenser and evaporator side.

For the GSHP, the evaporator temperature is linked to the ground water temperature. In the Beta-version simulation tool the ground water temperature has a sinus shaped, shown in Figure 8.

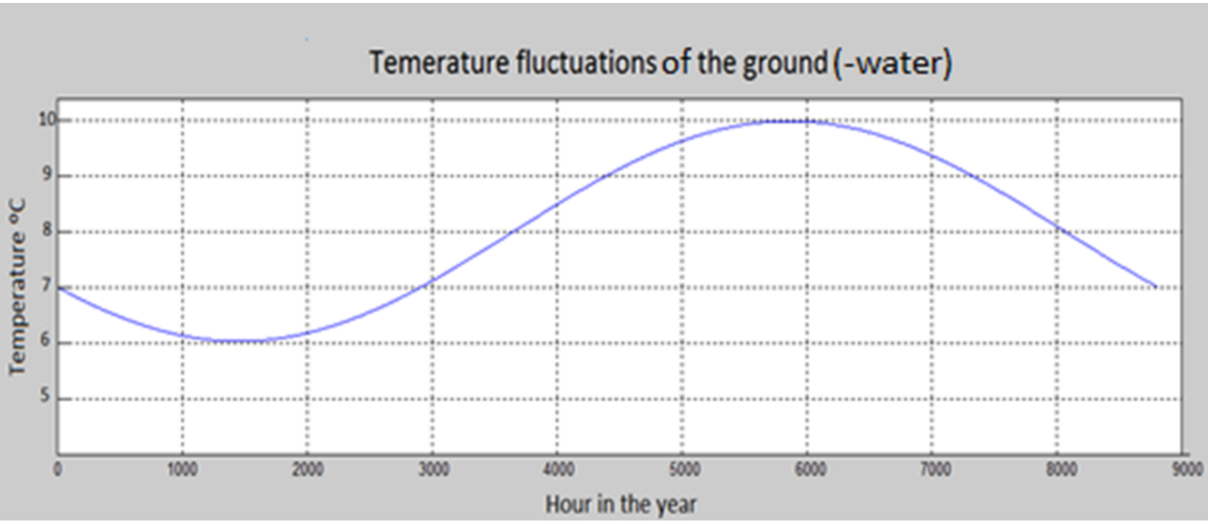


Figure 8 - Temperature fluctuations in the ground (-water) as it is considered in the Beta-version simulation tool. The peak is at the beginning of September, a shift to the right compared to outdoor air temperature.

As seen in Figure 8, the temperature used for evaporation is fluctuating over the year, with a peak in the beginning of September, a shift compared to the outdoor temperature. This is also the case for real ground temperature fluctuations. In reality the ground water temperature is rather stable over the year, but for energy wells the temperature is fluctuating (even more). The temperature fluctuation used is an attempt to find a median between the two. Temperature fluctuation behaviour in rock and ground is a complex science, and would call for competence within the field of geology. As a first approximation the simplification is therefore considered sufficient.

The length of the boreholes is directly linked to the size of the HP. There is a rule of thumb that it is possible to extract 30 W/m of borehole (Stene, 2012). The total length is found by subtracting compressor power from the condensation power at design conditions (Eq.6). The compressor power is found by dividing the inverse of the nominal COP times the nominal power on the (here a fixed default value) compressor energy efficiency (Eq.5). The borehole length must be found for every HP power coverage factor, and the cost is added to the HP.

$$E_{comp} = \frac{\left(\frac{Q_{hp,nom}}{COP_{nom}}\right)}{\eta_{comp}} \quad (Eq.5)$$

$$L_{borehole} = \frac{Q_{hp,nom} - E_{comp}}{e_{borehole}} \quad (Eq.6)$$

Table 8 - List of symbols for Eq.5 and Eq.6

E_{comp} = energy use compressor at nominal conditions
$Q_{hp,nom}$ = nominal heating capacity at nominal conditions
COP_{nom} = COP at nominal conditions
η_{comp} = compressor energy efficiency at nominal conditions.
$L_{borehole}$ = total length of the boreholes
$e_{borehole}$ = heat extraction from boreholes per meter

The water temperature on the condensation and evaporation side give the COP for the HP at the particular conditions, and the energy use is found by dividing the HP heating capacity by the COP (Eq.7). The SPF is found by adding the entire heating supply of the HP at an annual basis by the energy used to operate it (Eq.8).

$$\dot{E}_{hp} = \frac{\dot{Q}_{hp}}{COP} \quad (Eq.7)$$

$$E_{hp} = \frac{Q_{hp}}{\sum \dot{E}_{hp}} \quad (Eq.8)$$

Table 9 - List of symbols for Eq.7 and Eq.8

$\dot{E}_{hp}$ = input power to operate the HP	
$\dot{Q}_{hp}$ = HP power heating capacity	
COP = coefficient of performance	
E_{hp} = annual energy use to operate the HP	
Q_{hp} = annual HP thermal heat supply	

Cooling mode

For the cooling system another approach is used. As free cooling is the preferred way of system operation when cooling a building, the operational conditions are made dependent on this. How this is programmed is illustrated in Figure 9.

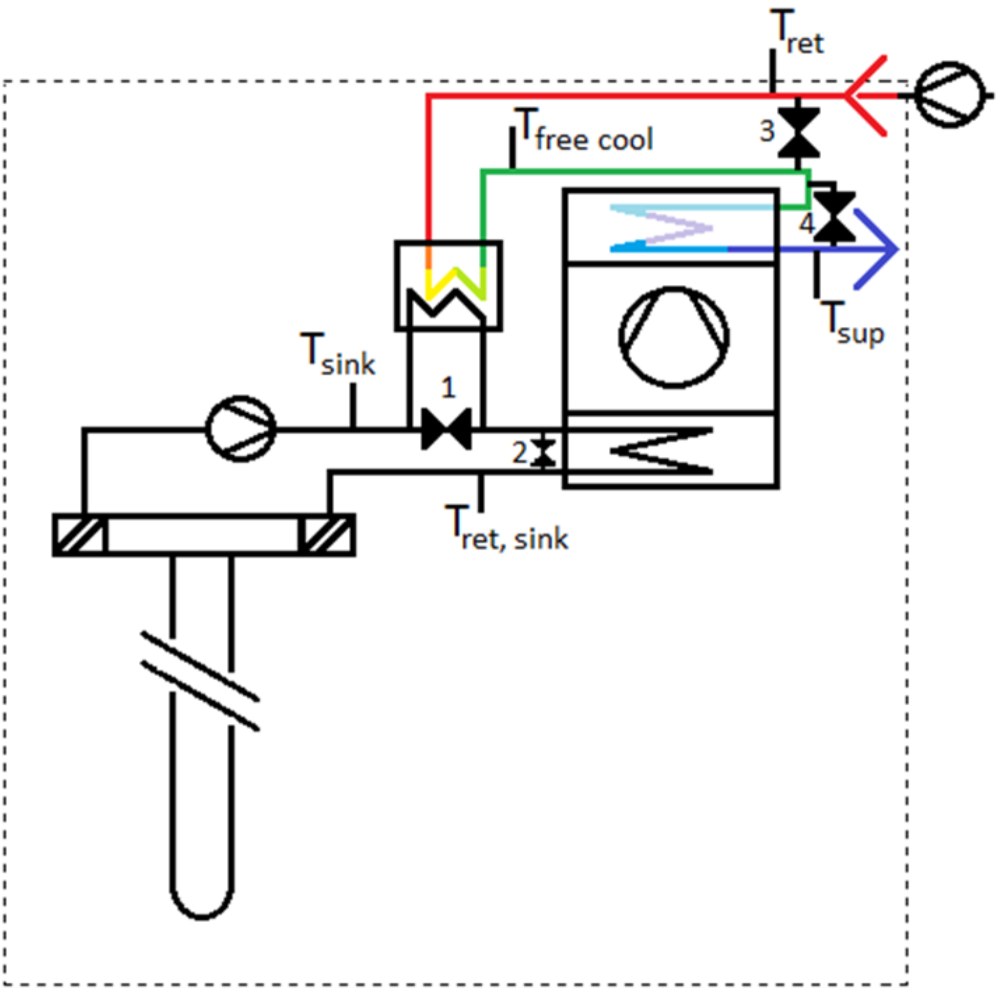


Figure 9 - Illustration of the HP in cooling mode.

Figure 9 is used to illustrate how the HP is programmed in cooling mode in the Beta-version simulation tool. (It is said that) if the sink temperature is 3K (a typical temperature difference water/water heat exchangers) lower than the return temperature, there is a potential for free cooling. If the free cooling is not enough, the HP must also be used. A default COP is then used (different for air and ground source, ref. Appendix 1) so that energy for cooling can be found. In combined free cooling and cooling mode, all the valves are closed. In free cooling mode, valve 1 and 3 are closed while 2 and 4 are open. In cooling mode (no free cooling potential), valve 1 and 3 are open, and 2 and 4 are closed. The entire cooling demand must be covered by either free cooling or/and cooling with the HP. There is no peak power system for the cooling system.

In reality the HP performance is related to the temperature lift from the evaporator side to the condenser side, but as the condenser temperature is affected by the free cooling, and $T_{ret,sink}$ is in practice influencing T_{sink}. The correct temperature conditions could be found, however, this is a complicated iteration process, with many variables. This could be introduced in the final simulation tool. Another concern for cooling (emission) systems is the risk of condensation (dew point). This is not implemented in the Beta-version, something that should/could be introduced in the final version.

2.3.8 PEAK POWER HEATING SYSTEM

The peak power heating system must provide the heating that is not covered by the HP. The annual installation cost is associated to the peak power technology covering the entire heat load, as it is also used as a backup system. The operational costs are associated to maintenance and energy cost. The maintenance cost is a percentage of the total capital cost, while the energy cost is linked to the efficiency of the system and the cost of the fuel (ref. Eq.9).

$$\dot{E}_{peak} = \frac{\dot{Q}_{peak}}{\eta_{peak}} \quad (Eq. 9)$$

Table 10 - List of symbols for Eq.9

$\dot{E}_{peak}$ = energy use to operate the peak power unit
$\dot{Q}_{peak}$ = peak power heat supply
η_{peak}= coefficient of performance

The default efficiencies for the three peak power systems introduced in the Beta-version simulation tool are the same as what is used in SIMIEN, Table 11:

Table 11 - The peak power technology efficiencies used in the Beta-version simulation tool.

Peak power heating technology	Efficiency (average value)
Electric boiler	0.90
Bio-boiler	0.73
Natural gas boiler	0.80

The efficiencies used in the Beta-version simulation tool are fixed values. However, for a real peak power system this efficiency will most likely change depending on the load. This could be implemented in the final simulation tool.

2.3.9 AUXILIARY ENERGY

In the project report, there is a Chapter about auxiliary energy, or parasitic loads. In the Beta-version simulation tool the work to pump water in the distribution system and for the brine in the ground source HP has been accounted for, using a fixed power per litre of fluid pumped per second [kW/(l/s)], the so-called specific pump power (SPP).

In the final simulation tool, the energy for e.g. defrosting or the evaporator (ASHP), fans and maybe an efficiency relation for the water flow and pump work could be introduced. The energy for pumps and fans should be considered taken up by the flowing fluid/air it is moving, something that is neglected in the Beta-version simulation tool.

2.3.10 ENERGY PRODUCING EQUIPMENT

In the Beta-version simulation tool, the only energy producing equipment that is introduced is PV panels. The magnitude of the installation is determined by the CO_2-emissions that must be counterbalanced for the operation of the buildings energy supply. By finding the specific energy production, kWh/kWp (input by the user, as it is dependent on location) and calculating the emission rate of the energy system solution, it is possible to find how much PV must be installed to counterbalance the emissions. The area can be found for both “optimum sloped” (40% inclination in Oslo, facing south) and horizontal PV solar panels. The default energy production for optimum sloped and horizontal PV used in the Beta-version simulation tool are; 781 kWh/kWp and 649 kWh/kWp respectively. The other information needed to calculate the magnitude of the PV installation is found in Appendix 1.

Figure 10 - Illustrates that sloped PV panels need more roof area than that of the actual cells. Depending on the optimum angular, the area needed on the roof will change. (Schueco, 2013)

An optimum sloped system is illustrated in Figure 10. For most ZEB the best option is to have the power generating panels on the roof, as façade mounted solutions tend to be more expensive and less effective. The roof area needed for the PV panels are greater for optimum sloped systems than that of horizontal ones, as the row of cells in front of another shades the incoming solar radiation for the one behind. The simulation tool is able to notify the user if the optimum sloped alternative needs more area than that of the available roof-area for the building. I the beta version simulation tool a ratio of 1/3 is used for optimum sloped PV and

1/1 for horizontal. If the area needed for PV exceeds this, the user is notified. In the case of a notification, a PV specialist should be contacted to find the exact area needed.

The CO_2-emission rate of the different energy sources, used in the Beta-version simulation tool that the PV must counterbalance, is listed in Table 12.

Table 12 - Table showing the CO_2-emissions from the energy sources included in the simulation tool (ProgramByggerne)

Energy source	Emission rate
Electricity	395 g/kWh
Bio fuel	14 g/kWh
Natural gas	211 g/kWh
The PV produces electricity and will not emit CO_2, but counterbalances by this rate	

In the final simulation tool, the cost of an installation to cover the entire operational energy (appliances and materials) of the building should also be introduced. Other power producing systems, e.g. micro CHP-plants and wind turbines may also be introduced.

2.3.11 Annual costs

The total annual cost is, as shown earlier in Figure 1, a combination of two cost parameters:

- Operational cost (includes maintenance cost here)
- Annual capital costs

Operational cost

The operational cost is linked to cost to operate the energy supply system and maintenance costs. All operational energy considered in the Beta-version simulation tool is listed under:

- Electric energy to operate the HP (heating and cooling mode)
- Energy to operate the peak power system
- Electric energy to operate pumps (heat sink/source and for water distribution in the building)

The maintenance cost is (here) linked to the following system implementations:

- HP and heat sink/source maintenance cost (fraction of capital cost)
- Peak power system maintenance cost (fraction of capital cost)
- PV panels (the maintenance cost is related to the area of installed PV)

As the peak power maintenance cost is linked to the capital cost, it will function as a “base cost”. This will bring up the operational cost with the same magnitude at all HP power coverage factors.

Annual capital costs

The annual capital costs are based on the annuity factor of the investment times the investment (Eq.10). The annuity factor is shown in Equation 10.1.

$$C_{annual.inv} = a \times I \quad (Eq.10)$$

$$a = \frac{r}{((1-r)^n - 1)} + r \quad (Eq.10.1)$$

Table 13 - List of symbols for Eq.10 and Eq.10.1

$C_{annual.inv}$ = Annual capital costs
I = capital cost
a = annuity factor
r = interest rate
n = expected lifetime of the investment

For all the investments, the interest rate is set to be the same. However, the expected lifetimes of the different subsystems are individual. The annuity factors for the different subsystems are thus not the same.

Many of the subsystems, and the investments needed for an energy system solution to work, are *not* linked to the HP power coverage factor, but to the design conditions. They will vary from energy supply strategy to strategy, but are costs that cannot be excluded, and will also function as “base costs”. Two examples are the peak power/back up technology and the heat emission strategy.

2.3.12 Domestic hot water

The domestic hot water (DHW) is calculated in a separate calculation loop. The idea is based on the one proposed in the project report, however, with some limitations. The additional cost is based on heating from the HP and/or the peak power system in a separate cost optimization loop. In this calculation loop, the cost of additional HP and peak power capacity is calculated; where the HP power coverage factor giving lowest annual cost is selected. The cost optimization calculation loop is essentially the same as the rest of the simulation tool, but with another temperature requirement. This is set to 65 ºC, the standard temperature to minimize the risk of disease by legionella. The additional cost of the DHW operational and annual capital cost is added to the annual cost of the other systems.

For the final simulation tool, other alternatives for DHW production should be included, as proposed in the project report. As the loop is separate from the other calculations, it is not necessarily bound by any particular system solution, as it is in the Beta-version simulation tool.

3. DEMONSTRATION OF THE BETA-VERSION SIMULATION TOOL

In the following Chapter, a proof of concept for the Beta-version simulation tool will be presented. The simulation tool can be used to find optimum HP power coverage factor and combination of sub-technologies (ref. 2.2, "The simulation boundaries") for a benchmark building. First, the benchmark building is presented. It is followed by simulation results (18 combinations time three building standards/concepts) and comments. A sensitivity analysis, to check the influence of some of the more important parameters for the calculations, is performed and commented. Finally a small test to check if night setback could be beneficial is conducted.

3.1 THE BENCHMARK BUILDING

The benchmark building is a fictive office building initially made for another Master thesis (Smedegård, 2012). The building is a free standing office building (no basement) located in Oslo. The building has a "normal" office design by today's standard (ref. Figure 11).

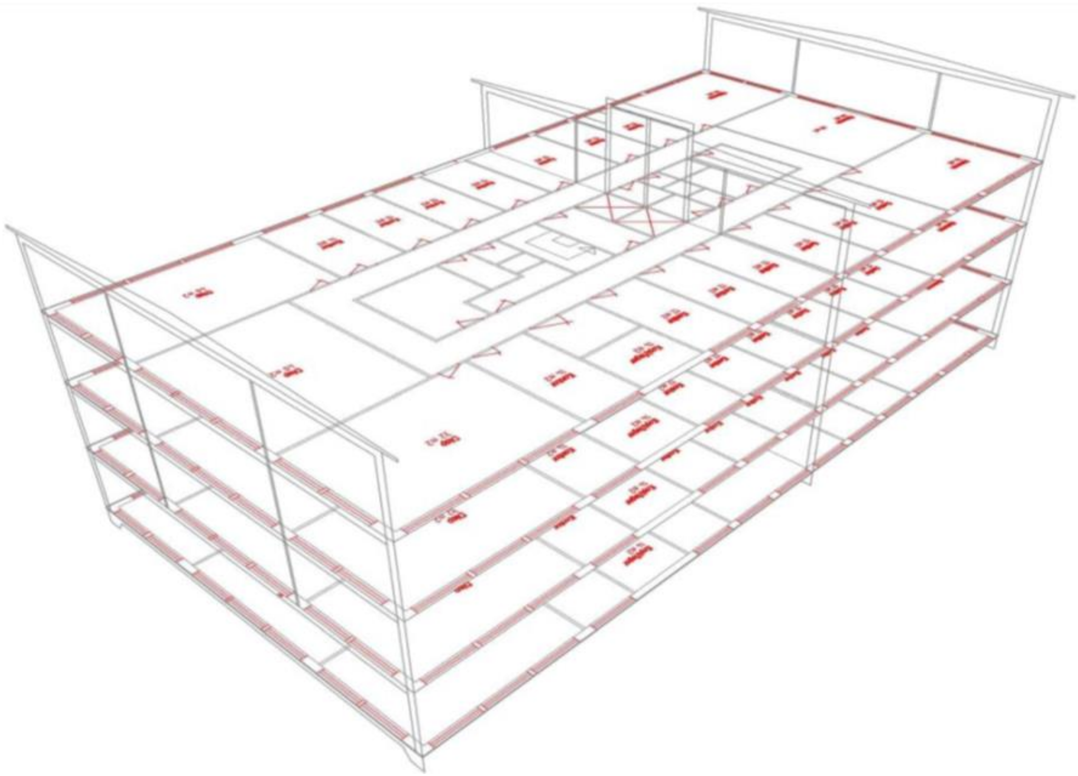


Figure 11 – Cross-Sectional view of the benchmark office building used to demonstrate the Beta-version simulation tool (Smedegård, 2012).

3.1.1 THE BUILDINGS SPECIFIC PROPERTIES

For energy and design conditions simulated in SIMIEN, the following building characteristics are used:

Building area and building components

The building has a gross area of 2500 m^2, calculated by NS 3940, and a heated space area of 2400 m^2 divided by 4 stories. The stories have a height of 3.2 m each, including floor slab. Figure 12 shows a plan drawing which gives the room separation in the building. The roof is 630 m^2, and is more or less horizontal (slope of 3 %).

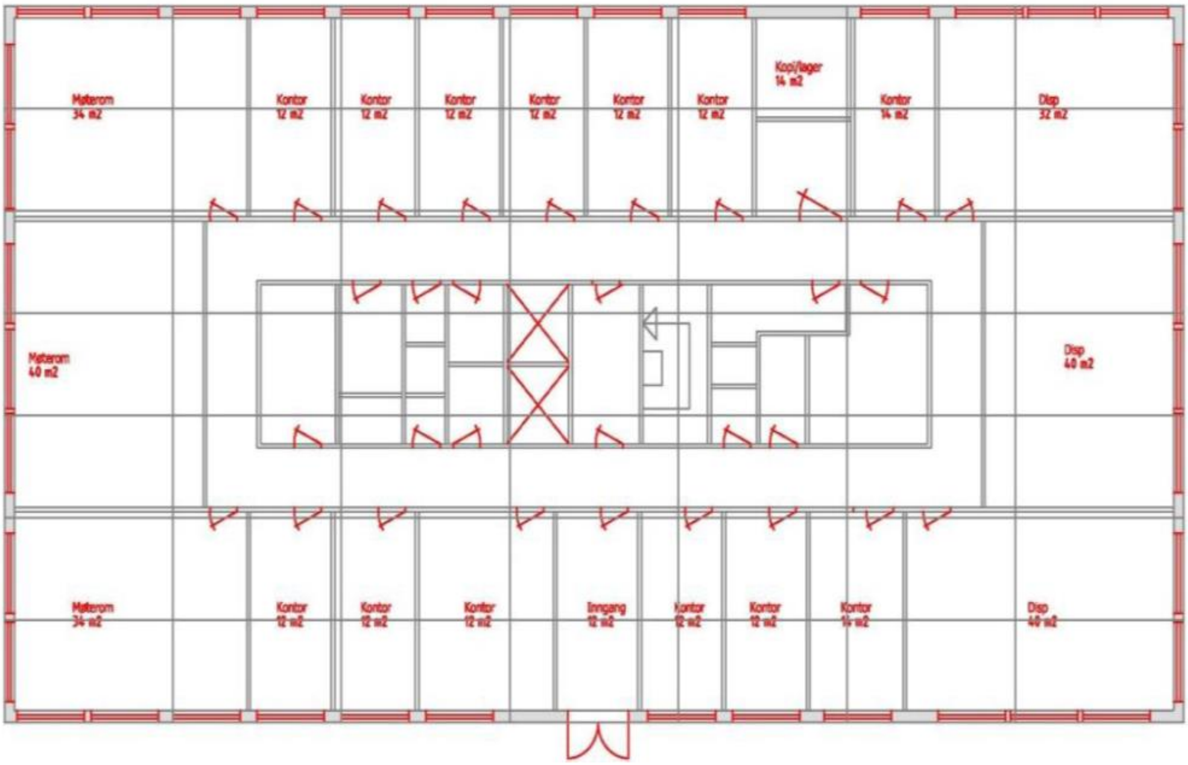


Figure 12 - Plan drawing of one of the floors in the building. This plan drawing is representative to the other floors as well (Smedegård, 2012).

Building construction

The building structure is “heavy”, by the classification given in NS 3031. In practice this means that the building has a large thermal mass. The building core, including well staircase and elevator shaft, is made of concrete. The floor slab is “hollow block floor”; elements of concrete. The office partition walls are not loadbearing, and are made of wood and other lightweight materials.

Windows

Every floor has 42 windows, altogether representing 20% of the net floor area.

Solar shading

The buildings original purpose was for testing heating systems, so the solar shading is quite extensive. The shading is done through:

- Structural canopy.
- External solar shading on west, east and south facing facades.
- High thermal building mass.

This is to prevent too high cooling loads, a favourable measure especially for ZEB and passive houses that aim to be energy efficient. The cooling load reduction is so extensive that all cooling is covered by the ventilation system. A change in cooling load for the use of this thesis (compared to the original SIMIEN setup) is obtained by allowing the indoor temperature to exceed 26 degrees for 50 hours over the TMY. In other words, there is no active room cooling in the benchmark building. The capital cost for this is also excluded in the results given, in Subchapter 3.2 “Simulation results”.

User patterns

The user pattern is “100% occupation during the working hours”, defined as 12 hours a day, 5 days a week, in accordance to NS 3031.

Air flow rate

In the strategy of building ventilation, user patterns and working hours are independent of the building standard. This is in order to see the influence that different building standards have on the building performance, when it comes to energy and power requirements. The airflow rate is calculated in accordance to NS-EN 15 251:

- Air flow rates in working hours are a function of person loads and material emissions.
- Air flow rates beyond work hours are a function of material emissions only.
- Supply air is always one degree below operational temperature under all circumstances.

The air change rate during working hours is 7 [m^3/h m^2] and off hours it is 5 [m^3/h m^2] for the TEK10 building, while it is 6 [m^3/h m^2] and 1,26 [m^3/h m^2] for the passive building and ZEB.

Internal loads and domestic hot water

Internal loads are in accordance to NS3031 and prNS3701[5], where values from prNS3701 are used for both passive house and ZEB in this thesis, the loads are (Table 14):

Table 14 - List of internal loads used in the simulations

Load	TEK10	Passive house and ZEB (prNS3701)
Person loads	4 W/m^2	4 W/m^2
Lighting	6.4 W/m^2	4 W/m^2
Equipment	11 W/m^2	6 W/m^2

[5] In connection with the preparation of NS 3701, SINTEF and “Norsk Lysteknisk Komité” have developed calculation assumptions and values for non-residential passive houses.

For domestic hot water the default used in SIMEN is applied, in accordance to NS 3031.

3.2 SIMULATION RESULTS

In the following Subchapter, the results produced from the simulations of the different building standards are presented. The benchmark building, described in Subchapter 3.1, is used for simulations, with the characteristics given by the standard (envelope properties, ref. TEK10 and NS3701). The SIMIEN-file is here produced without night setback[6] which is the appropriate operation for buildings using HPs for heating (Smedegård, 2013). Footnotes given in the Tables apply for all similar Tables. To avoid unnecessary breaks in the text, the explanations to the Tables and Figures are not consistent when it comes to structure. Sometimes it might come before the Table/Figure, sometimes after and sometimes between two Figures.

3.2.1 TEK 10 OFFICE BUILDING

First, the TEK10 building version of the benchmark building is simulated. This is the building closest related to the building standards applicable when the "rules of thumb" were developed (ref. 2.1, "Why a simulation tool?"). It is therefore presented first. This is to have an idea if the simulation tool gives valid results, and if the "rules of thumb" are targeted.

The data presented in Table 16 are for all 18 combinations of energy supply strategy used in the TEK10 office building, and some alternative ways to present the results are given in Table 16 and Figure 13. Table 15 shows the building specific input data used in the simulation. Figure 14, Figure 15 and Figure 16 show some power duration curves versus outdoor temperature for the simulated TEK10 building, while Figure 18 and Figure 17 show some typical cost optimization curves for some combinations.

Table 15 – The building specific input used in the Beta-version simulation tool for the TEK10 office building. As described, there is no room cooling, meaning there is no capital cost associated to a system for room cooling in the simulation (ref. 3.1.1, "The buildings specific properties"). The design conditions for heating are without internal loads or solar gain (net power).

TEK10 office building		
Design power for room heating	75.4	kW
Design power for ventilation heating	32.1	kW
Energy use for DHW	12000	kWh
Building size	2394.2	m2
Design power for room cooling	0	kW
Design power for ventilation cooling	19.2	kW
Energy recovery unit efficiency	0.8	-

[6] Night set-back: "A night setback system is used to control a heating system. A night setback system will lower the room temperature at night, which reduces heating costs. Office type buildings are not used at night, so lowering the room temperature will not cause discomfort" (Grundfos). It might however induce higher power requirements.

Table 16 – The HP energy and optimum coverage factor (heating mode only) for the TEK10 office building. Total annual cost is the sum of annual capital cost and operational cost, including DHW. Annual capital cost and operational cost given as explained in Section 2.3.11 (excl. DHW). All prices are in NOK. Annual CO_2-emissions are also given. The cheapest energy supply strategy on an annual basis is marked in green.

Characteristics for the different energy supply strategies in the TEK10 office building								
Energy supply strategy			HP cover-age factor [7]	Energy cover-age in percent (heating)[8]	Total annual cost (incl. DHW)	Annual invest-ment cost (excl. DHW)	Annual operatio-nal cost (excl. DHW)	Annual CO_2 emission (tons)
HP technology	Emission strategy	Peak power system	%	%	NOK/ year	NOK/ year	NOK/ year	t CO_2-/ year
ASHP	High temperature radiator system	Bio	43	71.7	278 970,-	168 430,-	104 260,-	21.55
		El.	43	71.7	186 660,-	93 134,-	87 262,-	40.21
		NG	55	80.7	206 540,-	107 360,-	92 296,-	31.26
	Low temperature radiator system	Bio	46	75.5	280 740,-	180 520,-	93 935,-	18.79
		El.	45	74.7	188 430,-	104 580,-	77 586,-	35.31
		NG	56	82.4	207 170,-	118 160,-	82 121,-	27.03
	Floor heating system [9]	Bio	48	78.8	286 780,-	196 740,-	83 744,-	15.81
		El.	48	78.8	194 460,-	121 440,-	66 762,-	29.77
		NG	58	85.2	211 700,-	134 380,-	70 434,-	22.51
GSHP	High temperature radiator system	Bio	33	69.7	289 380,-	177 750,-	105 340,-	21.43
		El.	33	69.7	197 060,-	102 450,-	88 341,-	41.38
		NG	45	83.8	216 130,-	122 400,-	86 851,-	30.78
	Low temperature radiator system	Bio	36	75.1	291 660,-	191 270,-	94 107,-	19.26
		El.	36	75.1	199 350,-	115 970,-	77 116,-	35.65
		NG	46	86.2	216 820,-	133 680,-	76 257,-	26.65
	Floor heating system	Bio	39	81.0	297 940,-	209 560,-	82 099,-	17.03
		El.	39	81.0	205 640,-	134 260,-	65 122,-	29.54
		NG	47	89.1	221 350,-	149 730,-	64 732,-	22.37

In Table 16, the simulation results are sorted by energy supply strategy. The energy supply strategy with lowest annual cost is marked in green. The system solution with lowest annual cost is the ASHP with high temperature radiator system and electric boiler for peak power. As seen from the Table, the operational cost is lower for the low temperature emission system, but as the capital cost is that much higher and it performs thus worse. The HP power coverage factor versus energy coverage corresponds well with theory initial assumptions. Lower supply

[7] Recommended by the simulation tool, as the percentage of net energy heating requirement (vent. + room)

[8] Domestic hot water and cooling is not included here

[9] Uses the same system for heating and cooling

temperature system also gives better energy coverage than high temperature systems, which is according to theory. Also the GSHP has higher energy coverage, per power coverage, than the ASHP, which is likely. However, the GSHP should have higher net energy coverage compared to the ASHP, but for some reason this is not the case for all system combinations.

Table 17 - Alternative way of presenting the results in Table 16. The results are the same, only sorted by annual cost.

Sorted by annual cost	Characteristics for the different energy supply strategies in the TEK10 office building								
	Energy supply strategy			Heat pump cover-age factor	Energy cover-age in percent (heating)	Total annual cost (incl. DHW)	Annual invest-ment cost (excl. DHW)	Annual operatio-nal cost (excl. DHW)	Annual CO_2 emission (tons)
	Heat pump tech-nology	Emission strategy	Peak power system	%	%	NOK/ year	NOK/ year	NOK/ year	t CO_2-/ year
1	ASHP	High temperature radiator system	El.	43	71,7	186 660,-	93 134,-	87 262,-	40.21
2	ASHP	Low temperature radiator system	El.	45	74,7	188 430,-	104 580,-	77 586,-	35.31
3	ASHP	Floor heating system	El.	48	78,8	194 460,-	121 440,-	66 762,-	29.77
4	GSHP	High temperature radiator system	El.	33	69.7	197 060,-	102 450,-	88 341,-	41.38
5	GSHP	Low temperature radiator system	El.	36	75,1	199 350,-	115 970,-	77 116,-	35.65
6	GSHP	Floor heating system	El.	39	81.0	205 640,-	134 260,-	65 122,-	29.54
7	ASHP	High temperature radiator system	NG	55	80.7	206 540,-	107 360,-	92 296,-	31.26
8	ASHP	Low temperature radiator system	NG	56	82.4	207 170,-	118 160,-	82 121,-	27.03
9	ASHP	Floor heating system	NG	58	85.2	211 700,-	134 380,-	70 434,-	22.51
10	GSHP	High temperature radiator system	NG	45	83.8	216 130,-	122 400,-	86 851,-	30.78
11	GSHP	Low temperature radiator system	NG	46	86.2	216 820,-	133 680,-	76 257,-	26.65
12	GSHP	Floor heating system	NG	47	89.1	221 350,-	149 730,-	64 732,-	22.37
13	ASHP	High temperature radiator system	Bio	43	71.7	278 970,-	168 430,-	104 260,-	21.55
14	ASHP	Low temperature radiator system	Bio	46	75.5	280 740,-	180 520,-	93 935,-	18.79
15	ASHP	Floor heating system	Bio	48	78.8	286 780,-	196 740,-	83 744,-	15.81
16	GSHP	High temperature radiator system	Bio	33	69.7	289 380,-	177 750,-	105 340,-	21.43
17	GSHP	Low temperature radiator system	Bio	36	75.1	291 660,-	191 270,-	94 107,-	19.26
18	GSHP	Floor heating system	Bio	39	81.0	297 940,-	209 560,-	82 099,-	17.03

In Table 17 an alternative way of presenting the results are given. Here they are sorted by annual costs. There is a distinct pattern what gives the alternative with lowest cost. The first thing worth noticing is that the peak power system is the most important factor for the ranking. The second most important factor is the HP technology, and the third most important is the supply temperature of the heat emission system. The annual operational costs does not change so much. It is also evident that the low temperature heat emission systems lead to lower operational costs. On the other hand, the annual capital cost varies more for the most expensive solutions are more than double the cost of those cheapest. The trend is that the most (investment) cost intensive alternatives gives worst solutions, when it comes to economic measures. It is worth noticing that these are the least CO_2-emission intensive alternatives as well. This is even more evident in Figure 13 on page 33.

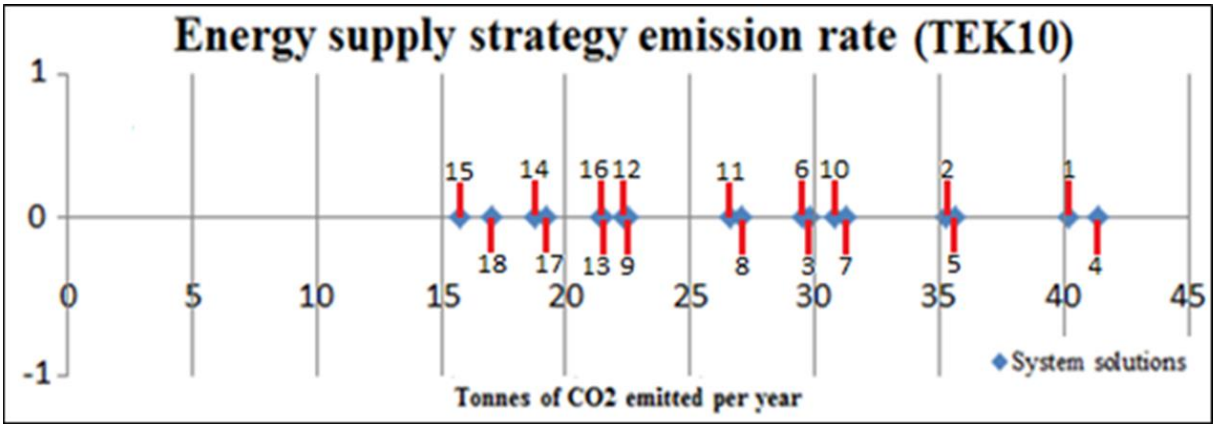


Figure 13 - The energy supply strategies, for the TEK10 office building, sorted by emission rate, where the upright corner is more emission intensive. The numbers indicate the ranking based on Table 17. The equipment to counter the CO_2 is not included in the annual cost here, and the Figure can only be used to subjectively select system solution based on emission rate.

Figure 13 illustrates the CO_2 emission rate of the different energy supply strategies, where the numbers refers to the ranking of the system solutions in Table 17. The most expensive solutions are the least emission intensive alternatives. An alternative way of presenting the results in the Table, is to have kg CO_2 emitted/year and m ^{2}. However, as the ratio is the same, the table would look almost the same. The reason why the ASHP, bio boiler peak power with floor heating is the least CO_2-intensive solutions (better than the GSHP, same peak and emitter), is because thermal energy covered by the HP emits more CO_2 that that covered by the bio boiler.

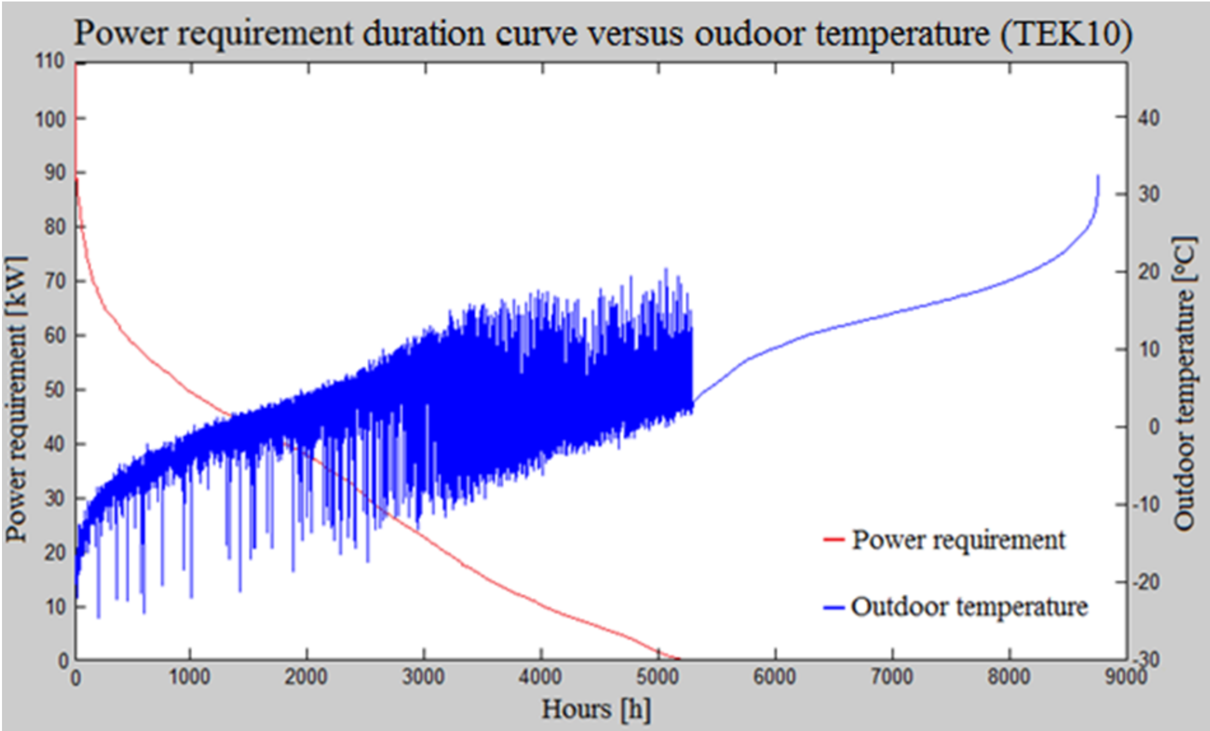


Figure 14 –The power requirement duration curve versus outdoor temperature for the TEK10 office building.

Figure 14 shows the power duration curve versus outdoor temperature, and as expected there is a strong correlation between them. The trend is that the power demand is in opposition to the outdoor temperature. However, as solar gains and internal loads influence the power requirement, the correlation is not 100 % in tune.

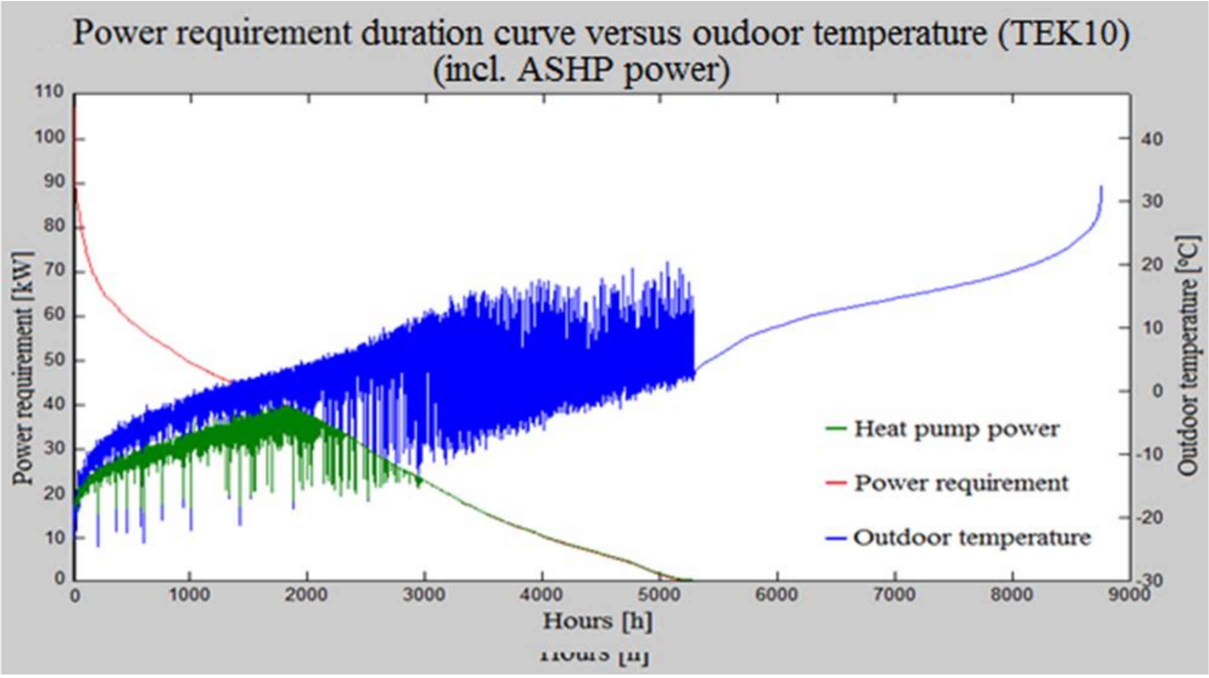


Figure 15 – The power requirement duration curve versus outdoor temperature and the HP power coverage factor for a typical ASHP. This particular one is for the low temperature radiator system, and the electric boiler is used as peak power.

Figure 15 and Figure 16 illustrate the available power of two different HPs at their optimum power coverage factor for two energy supply strategies (ref. Figure 15 and Figure 16). As expected the ASHPs power is closely related to the outdoor temperature, whereas the ground source HP is less influenced by this, and is therefore able to produce more power, even at low outdoor temperatures; and also confirming the claim that GSHPs have larger energy coverage at the same HP coverage factor.

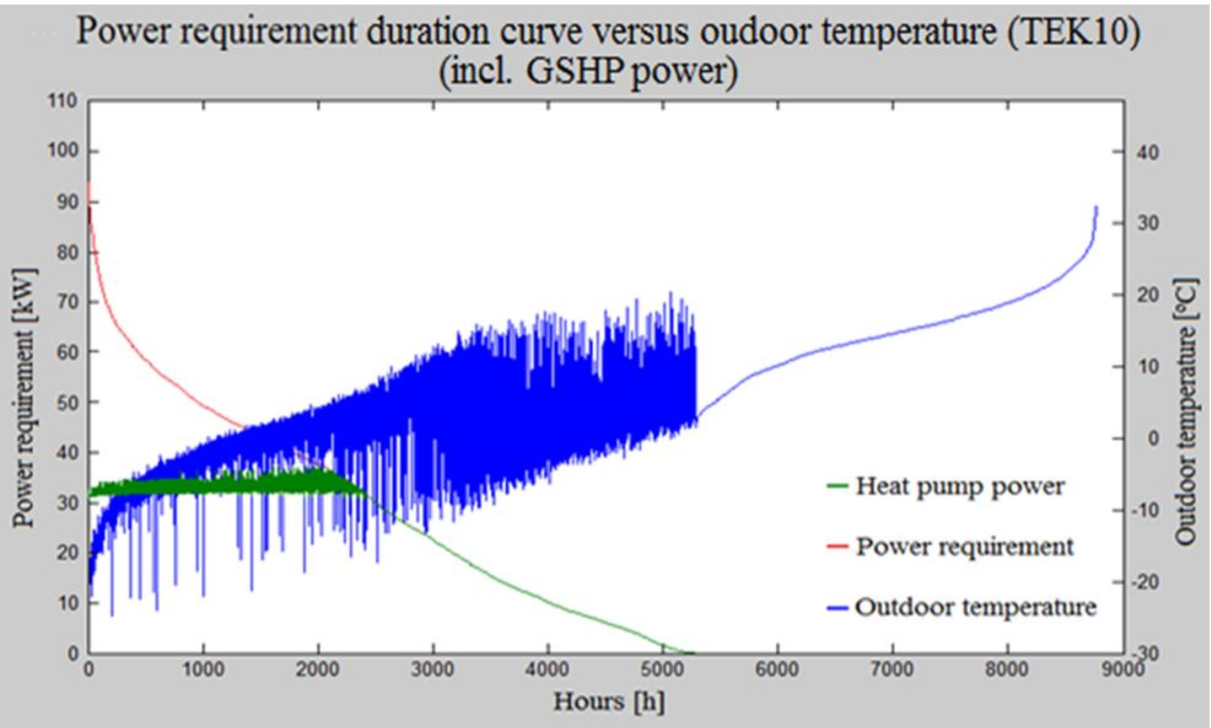


Figure 16 – The power requirement duration curve versus outdoor temperature and the HP power coverage factor for a typical GSHP. This particular one is for the low temperature radiator system, and the electric boiler is used as peak power.

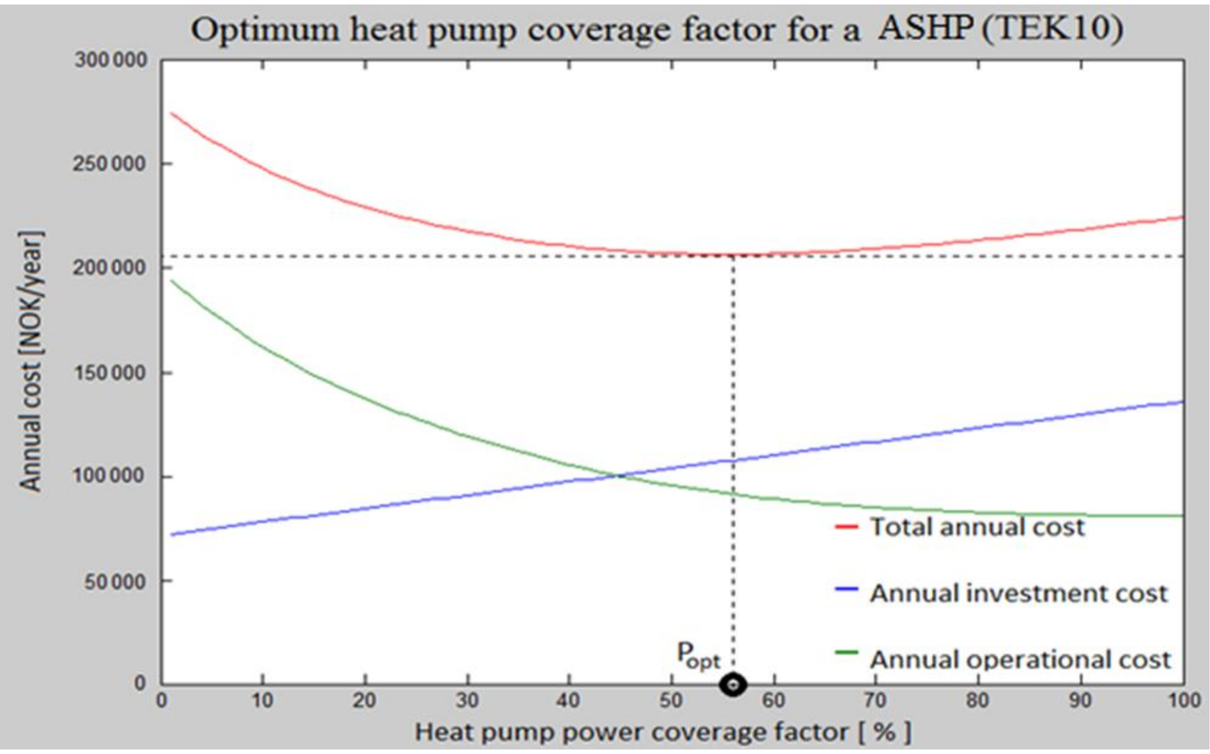


Figure 17 – Optimum HP power coverage factor given by a cost optimization curve, for ASHP, high temperature radiator system, and using electric boiler as peak power system.

Figure 17 and Figure 18 illustrate how the HP optimum power coverage factor is found. As explained in Chapter 2 the total annual cost curve is formed by the sum of annual capital cost and annual operational cost. The HP power coverage factor giving lowest annual costs is said to be the optimum. The shape of the curves will vary between the different energy supply strategies, but a trend is that the total annual cost curve is relatively symmetric on both sides of the optimum point. Furthermore a deviation from the optimum does not influence the cost significantly, unless the deviation is quite large (± 15%).

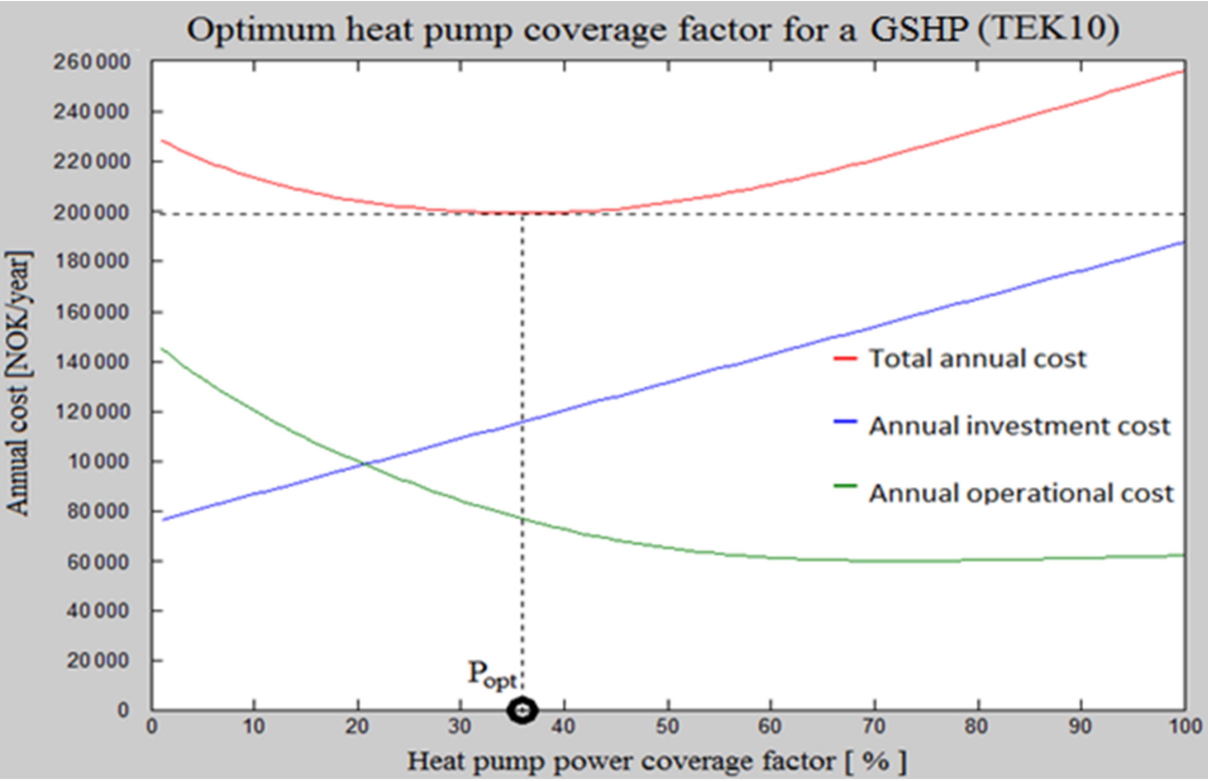


Figure 18 - Optimum HP power coverage factor given by a cost optimization curve for GSHP, high temperature radiator system, and using electric boiler as peak power system.

Summary

With some few exceptions (energy coverage for GSHP versus ASHP), the simulation results for the TEK10 office building are in line with what they should be in theory. This is an indication that the Beta-version simulation tool gives valid results. The energy supply strategies with lowest total annual cost are the ones with lowest annual capital cost. That is plausible as TEK10 is already an energy efficient building standard. It is therefore in line with the findings that have led to the Kyoto pyramid. The least CO_2-intensive energy supply strategies are also the most costly.

3.2.2 PASSIVE OFFICE BUILDING

The passive version of the benchmark office building has been simulated. The building standard is here equivalent to the ZEB concept in terms of envelope characteristics. The envelope of a passive building is often considered the starting point of a Zero Emission Building, and it is therefore appropriate to simulate this building standard.

The data presented in Table 19 is for all 18 combinations of energy supply strategy used in the passive office building. Table 18 shows the building specific input data used in the simulation. Figure 20, Figure 21 and Figure 22 show some power duration curves versus outdoor temperature for both the passive and the ZEB office building, as they both have the same shape due to equal building envelope (ZEB simulation results in Section 3.2.3). Also a comparison between passive/ZEB power duration curve and TEK10 power duration curve will be shown in Figure 23. The cost optimization curves are very similar for the passive office, as for the TEK10 office building. They are therefore omitted in this Section.

Table 18 – The building specific input used in the Beta-version simulation tool for the passive office building. As described, there is no load room cooling. The design conditions for heating are without internal loads or solar gain (net power).

TEK10 office building		
Design power for room heating	44.6	kW
Design power for ventilation heating	18.3	kW
Energy use for DHW	12000	kWh
Building size	2394.2	m2
Design power for room cooling	0	kW
Design power for ventilation cooling	14.4	kW
Energy recovery unit efficiency	0.85	-

Table 19 – The HP energy and optimum coverage factor (heating mode only) for the passive office building. Total annual cost is the sum of annual capital cost and operational cost, including DHW. Annual capital cost and operational cost given as explained in Section 2.3.11 (excl. DHW). All prices are in NOK. Annual CO_2-emissions are also given. The cheapest energy supply strategy on an annual basis is marked in green.

Characteristics for the different energy supply strategies in the Passive office building								
Energy supply strategy			HP cover-age factor	Energy cover-age in percent (heating)	Total annual cost (incl. DHW)	Annual capital cost (excl. DHW)	Annual operatio-nal cost (excl. DHW)	Annual CO_2 emission (tons)
HP technology	Emission strategy	Peak power system	%	%	NOK/ year	NOK/ year	NOK/ year	t CO_2-/ year
ASHP	High temperature radiator system	Bio	*23[10]	62.7	154 940,-	114 010,-	34 649,-	4.57
		El.	*23	62.7	100 920,-	69 940,-	24 718,-	11.27
		NG	30	73.7	110 820,-	74 017,-	30 584,-	8.10
	Low temperature radiator system	Bio	23	63.8	163 740,-	123 950,-	33 508,-	4.20
		El.	23	63.8	109 720,-	79 881,-	23 578,-	10.71
		NG	31	76.1	119 170,-	86 961,-	25 324,-	7.42
	Floor heating system	Bio	26	70.0	177 500,-	139 670,-	31 552,-	4.24
		El.	26	70.0	123 490,-	95 603,-	21 625,-	9.63
		NG	33	79.6	132 480,-	102 310,-	23 290,-	6.83
GSHP	High temperature radiator system	Bio	*23	73.4	159 230,-	120 420,-	32 575,-	5.46
		El.	*23	73.4	105 270,-	76 355,-	22 651,-	10.25
		NG	23	73.4	114 480,-	80 433,-	27 158,-	8.25
	Low temperature radiator system	Bio	*23	74.7	167 930,-	130 360,-	31 228,-	5.06
		El.	*23	74.7	113 920,-	86 297,-	21 364,-	9.61
		NG	25	78.6	122 920,-	91 684,-	24 355,-	7.51
	Floor heating system	Bio	*23	76.0	181 570,-	144 960,-	30 326,-	4.83
		El.	*23	76.0	127 560,-	100 890,-	20 403,-	9.14
		NG	26	81.8	136 260,-	106 930,-	22 443,-	6.98

In Table 19, the simulation results are sorted by energy supply strategy. The energy supply strategy with lowers annual cost is marked in green. This is the ASHP with high temperature radiator system and electric boiler for peak power, the same as for the TEK10 building. The HP power coverage factor versus energy coverage is way lower than for the TEK10 building, but this is expected. This is due to the power duration ratio of passive buildings (ref. Figure 23). Also here the low supply temperature emission systems gives better energy coverage

[10] All "heat pump coverage factors" marked with " * " have cooling system "override". The cooling system gives the power coverage factor (ref. Chapter 2). The same applies for all similar tables.

than the high temperature systems and the GSHPs have better energy coverage relative to the ASHPs, in good accordance with theory.

Table 20 - Alternative way of presenting the results in Table 19. The results are the same, but sorted by annual cost.

Sorted by annual cost	*Characteristics for the different energy supply strategies in the passive office building*								
	Energy supply strategy			Heat pump cover-age factor	Energy cover-age in percent (heating)	Total annual cost (incl. DHW)	Annual invest-ment cost (excl. DHW)	Annual operatio-nal cost (excl. DHW)	Annual CO_2 emission (tons)
	Heat pump tech-nology	Emission strategy	Peak power system	%	%	NOK/ year	NOK/ year	NOK/ year	t CO_2-/ year
1	ASHP	High temperature radiator system	El.	*23	62.7	100 920,-	69 940,-	24 718,-	11.27
2	GSHP	High temperature radiator system	El.	*23	73.4	105 270,-	76 355,-	22 651,-	10.25
3	ASHP	Low temperature radiator system	El.	23	63.8	109 720,-	79 881,-	23 578,-	10.71
4	ASHP	High temperature radiator system	NG	30	73.7	110 820,-	74 017,-	30 584,-	8.10
5	GSHP	Low temperature radiator system	El.	*23	74.7	113 920,-	86 297,-	21 364,-	9.61
6	GSHP	High temperature radiator system	NG	23	73.4	114 480,-	80 433,-	27 158,-	8.25
7	ASHP	Low temperature radiator system	NG	31	76.1	119 170,-	86 961,-	25 324,-	7.42
8	GSHP	Low temperature radiator system	NG	25	78.6	122 920,-	91 684,-	24 355,-	7.51
9	ASHP	Floorheating system	El.	26	70.0	123 490,-	95 603,-	21 625,-	9.63
10	GSHP	Floorheating system	El.	*23	76.0	127 560,-	100 890,-	20 403,-	9.14
11	ASHP	Floorheating system	NG	33	79.6	132 480,-	102 310,-	23 290,-	6.83
12	GSHP	Floorheating system	NG	26	81.8	136 260,-	106 930,-	22 443,-	6.98
13	ASHP	High temperature radiator system	Bio	*23	62.7	154 940,-	114 010,-	34 649,-	4.57
14	GSHP	High temperature radiator system	Bio	*23	73.4	159 230,-	120 420,-	32 575,-	5.46
15	ASHP	Low temperature radiator system	Bio	23	63.8	163 740,-	123 950,-	33 508,-	4.20
16	GSHP	Low temperature radiator system	Bio	*23	74.7	167 930,-	130 360,-	31 228,-	5.06
17	ASHP	Floorheating system	Bio	26	70.0	177 500,-	139 670,-	31 552,-	4.24
18	GSHP	Floorheating system	Bio	*23	76.0	181 570,-	144 960,-	30 326,-	4.83

In Table 20, the alternative way of presenting the results by annual cost does not show the same distinct pattern as for the TEK10 office building. However, as many of the HPs are dimensioned with respect to the cooling demand, the optimum is shifted and is influencing the results. The annual capital cost is the most influencing on the total cost. The systems with low capital cost are top ranked, while the annual operational cost does not vary so much. The same trend as for the TEK10 office building, with respect to the CO_2-emissions, where the most costly alternatives are best is also applicable here. This is illustrated in Figure 19.

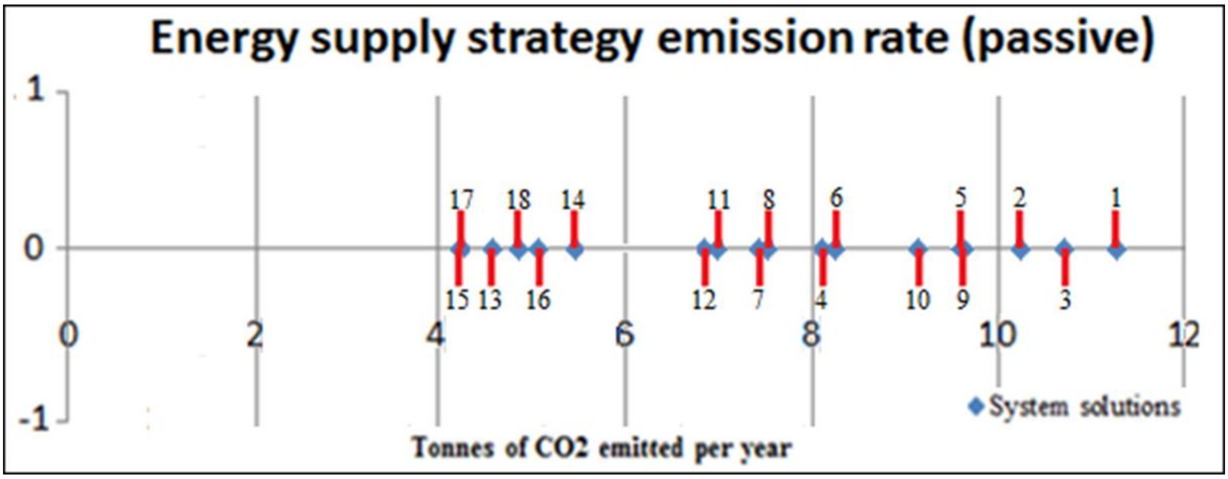


Figure 19 - Energy supply strategies for the passive office sorted by emission rate. The numbers indicate the ranking based on Table 19. The equipment to counterbalance the CO_2 is not included in the annual cost here, and the Figure can only be used to subjectively select system solution based on emission rate.

Figure 19 illustrates the CO_2 emissions of the different energy supply strategies, where the numbers refers to the ranking of the system solutions in Table 20. The most expensive solutions are the least emission intensive alternatives.

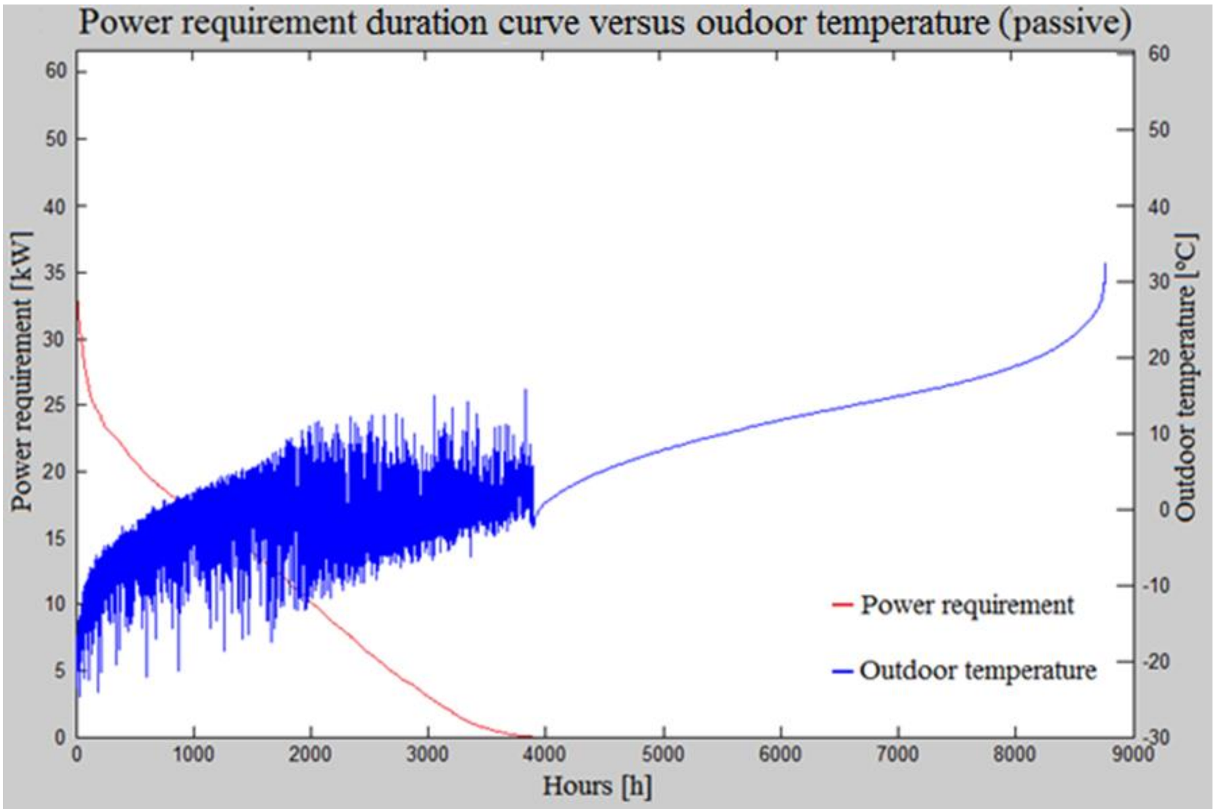


Figure 20 - Power requirement duration curve versus outdoor temperature for the passive and ZEB office building.

Figure 20 shows the power duration curve versus actual outdoor temperature. As expected, also for the passive office building, there is a strong correlation between the two. The trend is that the power demand is inversely proportional with the outdoor temperature. However, as solar gains and internal loads influence the power requirement, the correlation is not 100 % in tune. It is also worth noticing that the heating season is noticeably shorter for the passive office building (about 3900 hours versus about 5200 for TEK10), which also is expected. As seen, even at outdoor temperatures below zero degrees there are times that there is no heating requirement, which tells us that the envelope is very efficient. Also design power is relatively high compared to the actual power requirements.

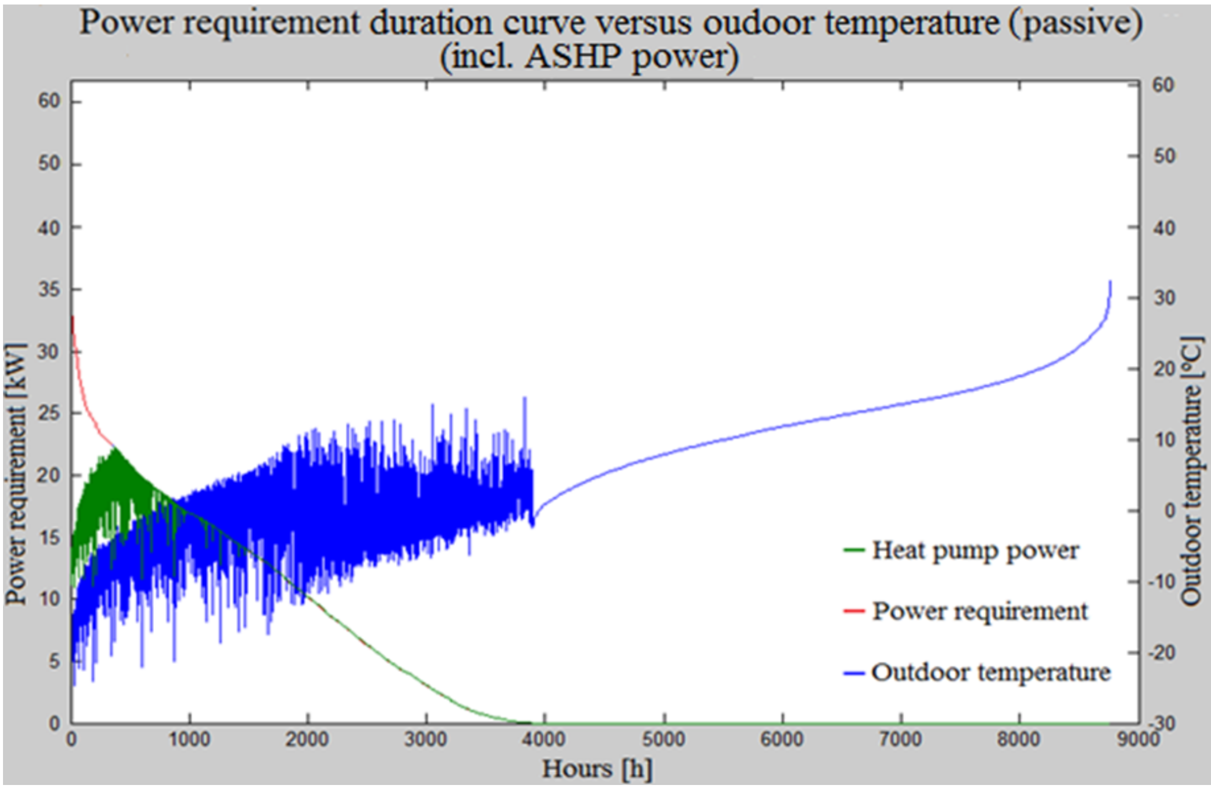


Figure 21 - Power requirement duration curve versus outdoor temperature with the HP power coverage factor for a typical air source system. This particular one is for the high temperature radiator system, using electric boiler for peak power, for the ZEB version (ref. Table 22).

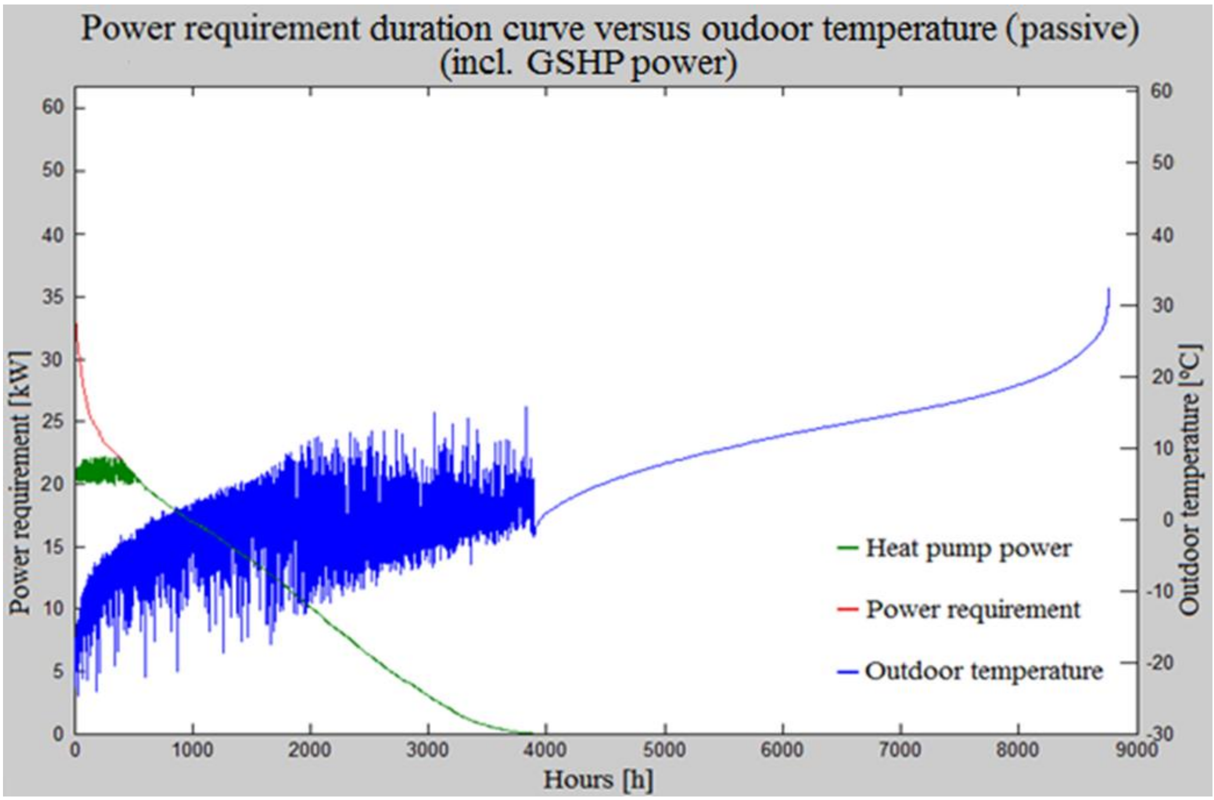


Figure 22 - Power requirement duration curve versus outdoor temperature with the HP power coverage factor for a typical ground source system. This particular one is for the high temperature radiator system, using electric boiler for peak power, for the ZEB version (ref. Table 22).

Figure 21 and Figure 22 illustrate the available power of two different HPs at their optimum power coverage factor for two energy supply strategies. As expected, the ASHP's heating capacity is closely related to the outdoor temperature, whereas the GSHP is almost not influenced by this. The GSHP is therefore able to maintain the heating capacity, even at low outdoor temperatures. It is also confirming the fact that GSHPs have larger energy coverage at the same HP power coverage factor.

The cost optimization curves are, as previously stated, very similar to the ones for the TEK10 office building and illustrations are therefore omitted for the passive office building.

Figure 23 shows the two different power duration curves applied in this thesis. As seen, the design power requirement versus the general power requirement is relatively higher for the passive/ZEB building compared to the TEK10. This explains why low power coverage factor for the HP gives high energy coverage in the passive office building.

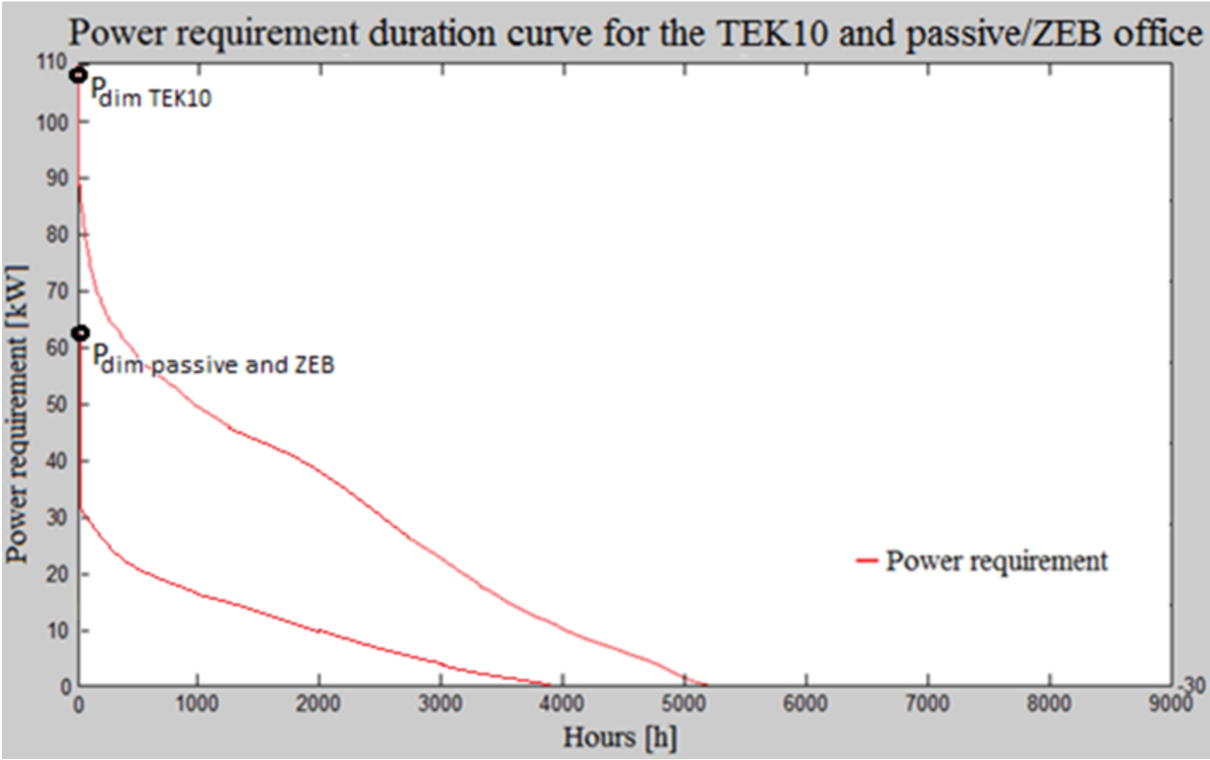


Figure 23 – Power duration curve for passive/ZEB and TEK10 office building. The TEK10 is the upper one and passive/ZEB is the bottom one. The design conditions for heating are without internal loads or solar gain (net power).

Summary

The simulation results for the passive office building show that moderate power coverage factor gives high energy coverage, something that is supported by Figure 20 to Figure 23. Also the cooling capacity is dominating the coverage factor for most of the energy supply strategies. If measures to reduce the cooling requirements could be found, the HP power coverage factor could be even lower. As for the TEK10 office building, the annual capital cost is the main factor influencing the total cost. This makes sense since there is even lower operational heating demand in a passive building compared to TEK10. The least CO_2-

intensive supply strategies are most costly in these simulations, e.g. the bio-boiler peak power system.

3.2.3 ZERO EMISSION OFFCIE BUILDING

The ZEB version of the benchmark office building has been simulated. The same SIMIEN-file as for the passive office was used, as the envelope and operation for the two concepts are here considered the same. The only difference is the additional cost for the PV panels to counterbalance the CO_2 emissions associated to operation of HVAC and DHW systems.

The data presented in Table 22, the energy supply strategies have “optimum sloped” PV. Table 21 shows the building specific input data used in the simulation, which are the same as for the passive office. The power requirement duration curve versus outdoor temperature is the same as for the ZEB and is omitted here. Figure 25 and Figure 26 are cost optimization curves based on the lowest annual cost. The data in Table 24 are for horizontal PV.

Table 21 – Building specific input used in the Beta-version simulation tool for the Zero Emission office. As described, there is no room load cooling. The design conditions for heating are without internal loads or solar gain (net power).

ZEB office building		
Design power for room heating	44.6	kW
Design power for ventilation heating	18.3	kW
Energy use for DHW	12000	kWh
Building size	2394.2	m2
Design power for room cooling	0	kW
Design power for ventilation cooling	14.4	kW
Energy recovery unit efficiency	0.85	-

Table 22 – The HP energy and optimum coverage factor (heating mode only) for the ZEB office building. Total annual cost is the sum of annual capital cost and operational cost, including DHW. Annual capital cost and operational cost given as explained in Section 2.3.11 (excl. DHW). All prices are in NOK. Annual CO_2-emission and optimum sloped PV area is also given. The cheapest energy supply strategy on an annual basis is marked in green.

Characteristics for the different energy supply strategies in the ZEB office building "optimum sloped" PV solar panels									
Energy supply strategy			HP coverage factor	Energy coverage in percent (heating)	Total annual cost (incl. DHW)	Annual capital cost (excl. DHW)	Annual operational cost (excl. DHW)	Annual CO_2 emission (tons)	Area of photovoltaic incl. DHW
HP technology	Emission strategy	Peak power system	%	%	NOK/ year	NOK/ year	NOK/ year	t CO_2-/ year	m^2 PV
ASHP	High temperature radiator system	Bio	*23	62.7	202 760,-	154 990,-	35 464,-	4.57	110.6
		El.	46	88.1	215 300,-	165 630,-	22 763,-	8.68	214.4[11]
		NG	37	81.5	207 780,-	156 960,-	26 622,-	7.89	194.3
	Low temperature radiator system	Bio	*23	63.8	208 650,-	162 090,-	34 257,-	4.20	101.7
		El.	50	90.9	216 170,-	168 630,-	20 633,-	7.58	187.9
		NG	41	85.8	210 010,-	161 950,-	23 866,-	7.05	174.1
	Floor heating system	Bio	*23	64.8	221 000,-	175 230,-	33 466,-	4.00	97.1
		El.	53	93.1	222 890,-	177 190,-	18 796,-	6.64	165.5
		NG	44	88.8	218 110,-	172 230,-	21 686,-	6.34	157.0
GSHP	High temperature radiator system	Bio	*23	73.4	214 070,-	168 220,-	33 584,-	5.46	132.0
		El.	38	93.7	215 810,-	168 200,-	20 709,-	8.03	198.6
		NG	32	88.0	210 860,-	162 630,-	24 030,-	7.71	190.0
	Low temperature radiator system	Bio	*23	74.7	219 590,-	175 100,-	32 189,-	5.06	122.3
		El.	38	94.6	217 390,-	171 650,-	18 840,-	7.18	178.3
		NG	33	90.3	213 420,-	167 430,-	21 793,-	6.95	171.8
	Floor heating system	Bio	*23	76.0	231 400,-	187 910,-	31 186,-	4.83	116.7
		El.	39	96.2	224 970,-	180 880,-	17 182,-	6.39	159.4
		NG	35	93.5	221 850,-	178 110,-	19 547,-	6.27	155.4

In Table 22, simulation results with optimum sloped PV to counter CO_2-emissions are shown sorted by energy supply strategy. For both the TEK10 and the passive office, ASHP, high temperature radiator system and electric boiler give the lowest annual cost. For the ZEB, the electric boiler is replaced by the bio-boiler, one of the most costly systems for the TEK10 and passive version of the office building. The power coverage factor and energy coverage seems plausible, as the design power is relatively high for the passive/ZEB office building

[11] Over area is over the 1/3 limit. The roof is 630 m^2, so if the area exceeds 210 m^2 the user is notified.

(ref. Section 3.2.2, “Summary”). Many of the solutions are near the threshold limit of PV area of 1/3 whereas the ASHP, high temperature radiator system using el. boiler as peak is over.

Table 23 - Alternative way of presenting the results in Table 22. The results are the same, but sorted by annual cost.

Sorted by annual cost	*Characteristics for the different energy supply strategies in the ZEB office building “optimum sloped” photovoltaic solar panels*									
	Energy supply strategy			Heat pump cover-age factor	Energy cover-age in percent (heating)	Total annual cost (incl. DHW)	Annual investment cost (excl. DHW)	Annual operatio-nal cost (excl. DHW)	Annual CO_2 emission (tons)	Area of photo-voltaic incl. DHW
	Heat pump technology	Emission strategy	Peak power system	%	%	NOK/ year	NOK/ year	NOK/ year	t CO_2-/ year	m^2 PV
1	ASHP	High temperature radiator system	Bio	*23	62.7	202 760,-	154 990,-	35 464,-	4.57	110.6
2	ASHP	High temperature radiator system	NG	37	81.5	207 780,-	156 960,-	26 622,-	7.89	194.3
3	ASHP	Low temperature radiator system	Bio	*23	63.8	208 650,-	162 090,-	34 257,-	4.20	101.7
4	ASHP	Low temperature radiator system	NG	41	85.8	210 010,-	161 950,-	23 866,-	7.05	174.1
5	GSHP	High temperature radiator system	NG	32	88.0	210 860,-	162 630,-	24 030,-	7.71	190.0
6	GSHP	Low temperature radiator system	NG	33	90.3	213 420,-	167 430,-	21 793,-	6.95	171.8
7	GSHP	High temperature radiator system	Bio	*23	73.4	214 070,-	168 220,-	33 584,-	5.46	132.0
8	ASHP	High temperature radiator system	El.	46	88.1	215 300,-	165 630,-	22 763,-	8.68	214.4
9	GSHP	High temperature radiator system	El.	38	93.7	215 810,-	168 200,-	20 709,-	8.03	198.6
10	ASHP	Low temperature radiator system	El.	50	90.9	216 170,-	168 630,-	20 633,-	7.58	187.9
11	GSHP	Low temperature radiator system	El.	38	94.6	217 390,-	171 650,-	18 840,-	7.18	178.3
12	ASHP	Floor heating system	NG	44	88.8	218 110,-	172 230,-	21 686,-	6.34	157.0
13	GSHP	Low temperature radiator system	Bio	*23	74.7	219 590,-	175 100,-	32 189,-	5.06	122.3
14	ASHP	Floor heating system	Bio	*23	64.8	221 000,	175 230,-	33 466,-	4.00	97.1
16	GSHP	Floor heating system	NG	35	93.5	221 850,-	178 110,-	19 547,-	6.27	155.4
15	ASHP	Floor heating system	El.	53	93.1	222 890,-	177 190,-	18 796,-	6.64	165.5
17	GSHP	Floor heating system	El.	39	96.2	224 970,-	180 880,-	17 182,-	6.39	159.4
18	GSHP	Floor heating system	Bio	*23	76.0	231 400,-	187 910,-	31 186,-	4.83	116.7

In Table 23, the alternative way of presenting the results by annual cost, shows that the previous trends for the TEK10 and passive buildings does not apply for the ZEB. The more CO_2 -intensive alternatives are being “punished”, as they call for larger emission counter-balancing PV-cells. This is actually disadvantageous for the GSHPs in combination with bio-boiler, as electricity used in the HP calls for more PV compared to the smaller energy coverage by the ASHPs in combination with bio-boiler. For the passive office building, most of the energy supply strategy system solutions have a HP power coverage factor overridden by the cooling demand. For the ZEB, higher power coverage factor is seen for the more CO_2-intensive peak power systems (to reduce the CO_2-emissions and thus PV-cost). The span between the most costly and least costly alternative has gone significantly down. For the TEK10 and passive office the top and bottom of the ranking is differentiated by a factor of about two, whereas it for the ZEB is only about 15% difference.

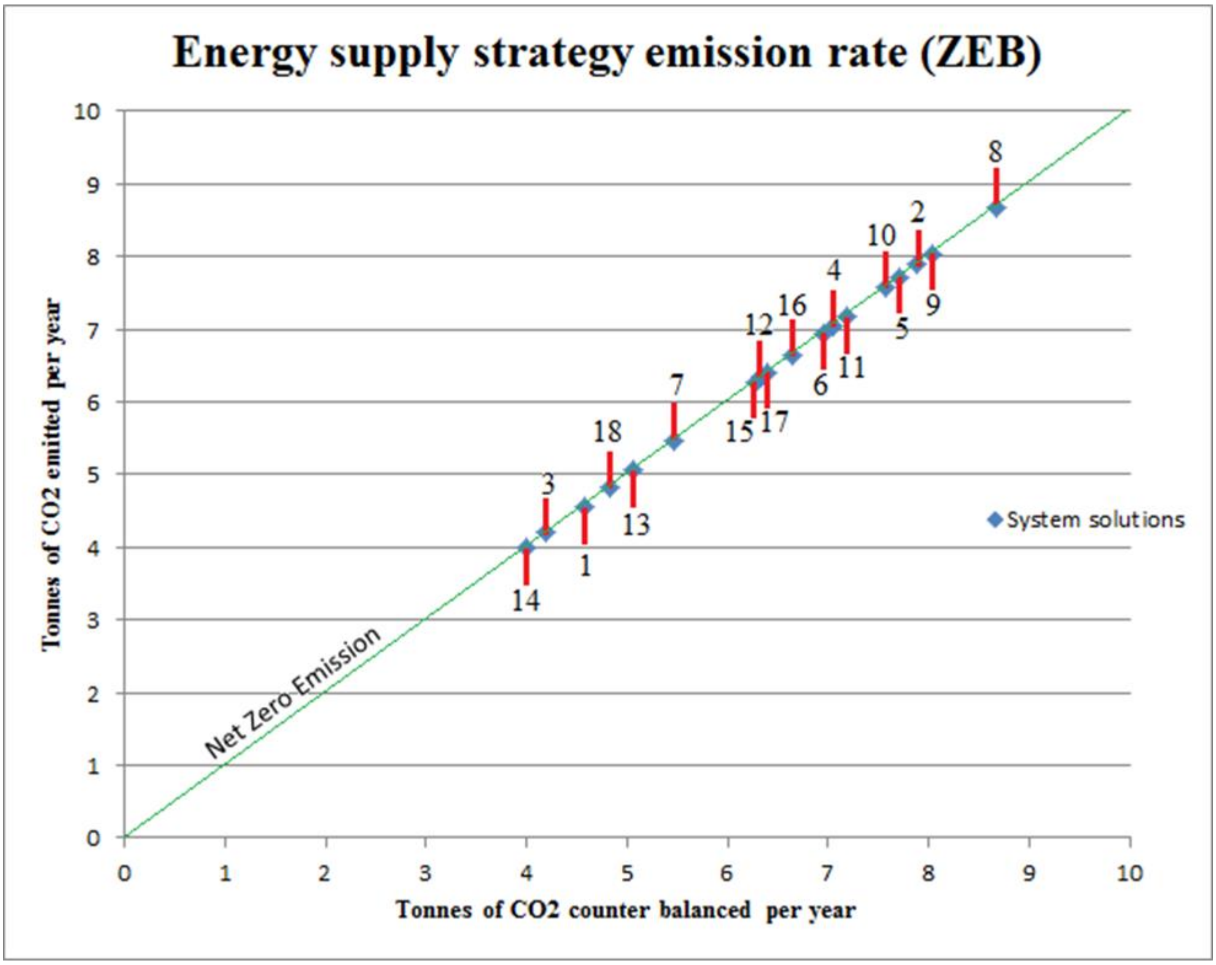


Figure 24 - Energy supply strategies for the ZEB office sorted by emission rate, where the upright corner is more emission intensive. The numbers indicate the ranking based on Table 23. The equipment to counterbalance the CO_2 is included in the annual cost.

Table 24 illustrates the CO_2 emission rate of the different energy supply strategies where the numbers refers to the ranking of the system solutions in Table 23. For both the TEK10 and the passive offices, the trend is that the less expensive energy supply systems have more emissions whereas the more expensive ones have lower emissions. For the ZEB concept, there is no evident trend. However, the emissions due to operation of the building are on average lower for the ZEB building than the two other building standards.

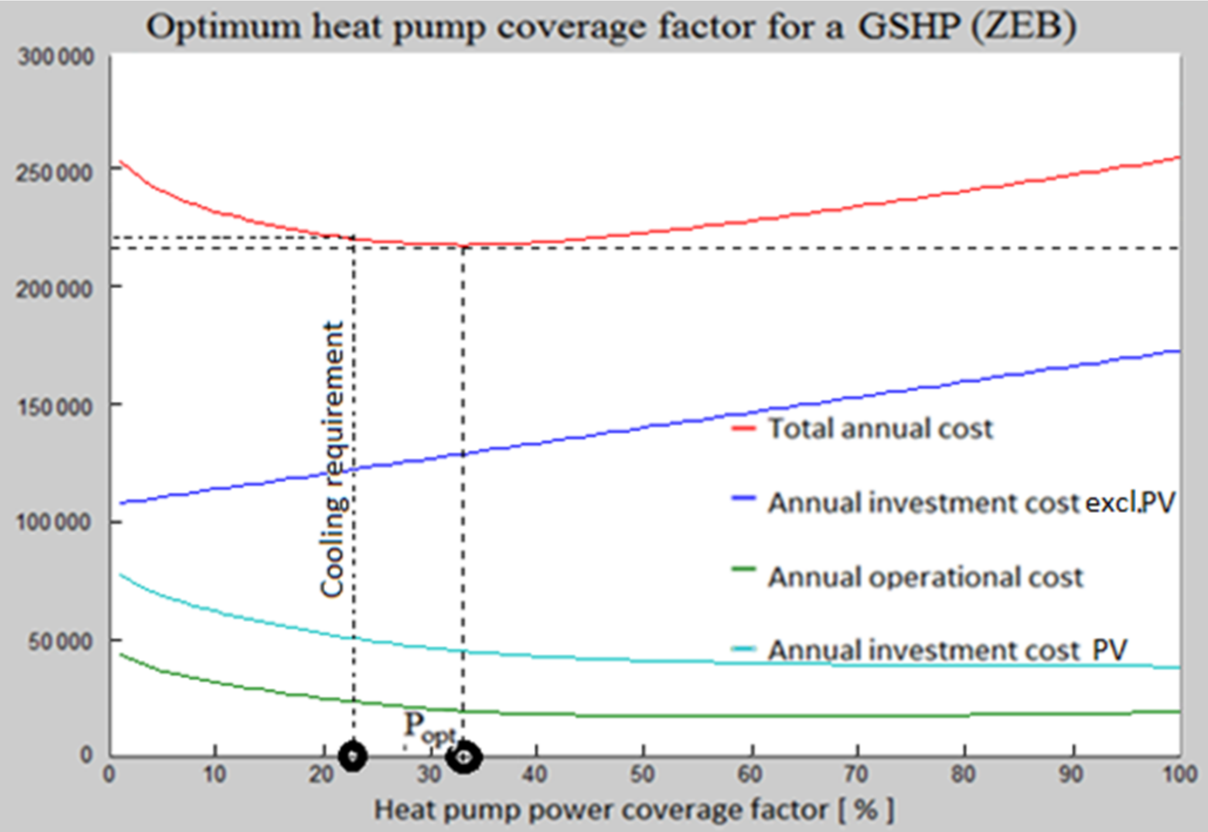


Figure 25 - Optimum HP power coverage factor given by cost optimization curve for GSHP, floor heating system and Natural Gas boiler as peak power system in the ZEB office building.

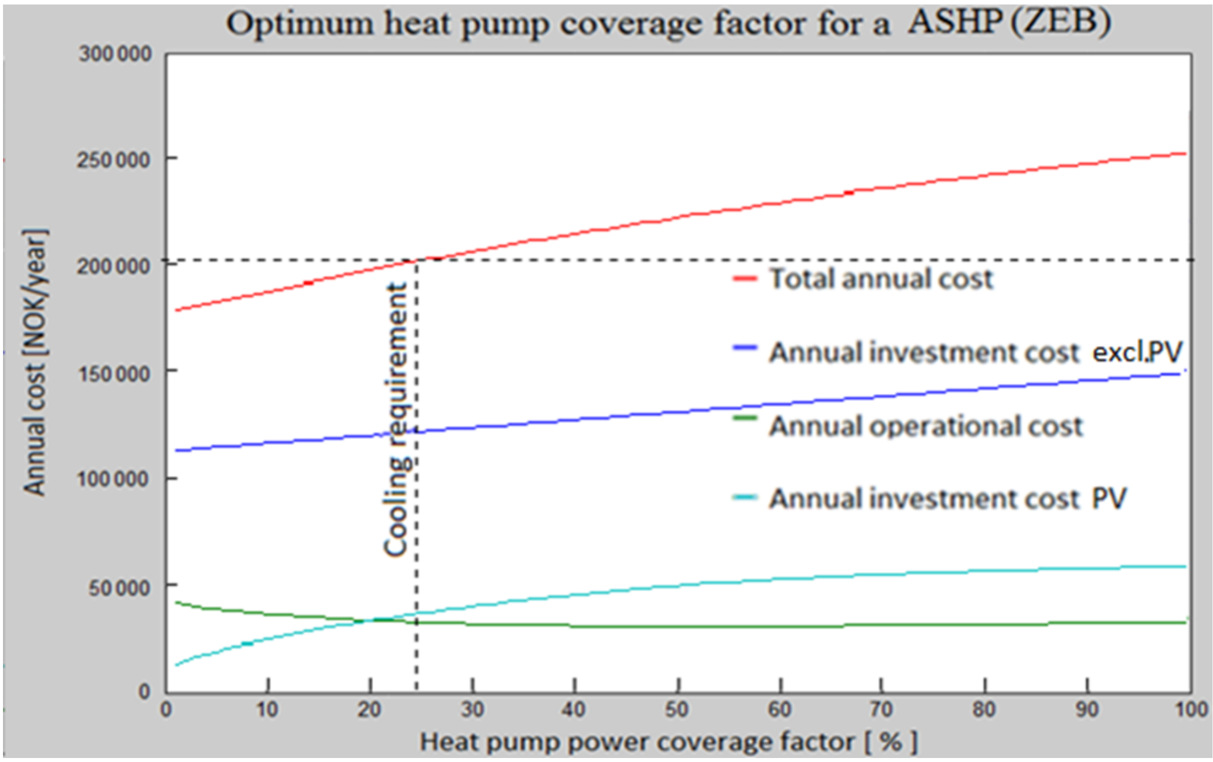


Figure 26 - Optimum HP power coverage factor given by cost optimization curve for ASHP, high temperature radiator system and bio-boiler as peak power system in the ZEB office building.

Figure 25 and Figure 26 show the cost optimization curve for two energy supply strategies. The annual operational cost curve is basically the same as for the TEK10 and passive office. However, the introduction of PV changes the situation. The relatively CO_2-emission intensive NG peak power system poses a disadvantage for low heat pump power coverage factor (ref. Figure 25) whereas the low CO_2-emissions from the bio-boiler give an advantage for low heat pump coverage (ref. Figure 26).

Figure 25 shows a cost optimization using the relatively CO_2-intensive natural gas boiler. It is obvious that low HP power coverage factor gives high cost as this calls for more PV. As the HP power coverage factor goes up, the energy covered by the HP becomes more and more significant, and thus the CO_2-emissions and need for PV is reduced. Towards 100% HP power coverage factor, the HP capital cost is the dominant one.

Figure 26 shows a cost optimization using the bio-boiler as peak power system characterized by very low CO_2-emissions. Here low HP power coverage factor is an advantage, as this call for almost no PV. However, as the HP is dimensioned to cover the cooling power the system dimensions are more to the right than the lowest point of the curve. Solutions to this problem will be discussed in Chapter 5, “Future work”.

Table 24 – The HP energy and optimum coverage factor (heating mode only) for the ZEB office building. Total annual cost is capital cost and operational cost, inclusive DHW. Annual capital cost and operational cost given as explained in Section 2.3.11 (excl. DHW). All prices are in NOK. Annual CO_2-emission and horizontal PV area are also given. The cheapest energy supply strategy on an annual basis is marked in green.

Characteristics for the different energy supply strategies in the ZEB office building "horizontal" PV solar panels									
Energy supply strategy			HP cover-age factor	Energy cover-age in percent (heating)	Total annual cost (incl. DHW)	Annual capital cost (excl. DHW)	Annual operatio-nal cost (excl. DHW)	Annual CO_2 emission (tons)	Area of photo-voltaic incl. DHW
HP technology	Emission strategy	Peak power system	%	%	NOK/ year	NOK/ year	NOK/ year	t CO_2-/ year	m^2 PV
ASHP	High temperature radiator system	Bio	*23	62.7	211 260,-	162 720,-	35 629,-	4.57	133.0
		El.	49	89.7	237 390,-	183 280,-	23 017,-	8.55	254.3
		NG	38	82.4	227 160,-	172 860,-	26 688,-	7.88	233.3
	Low temperature radiator system	Bio	*23	63.8	216 560,-	169 230,-	34 409,-	4.20	122.2
		El.	53	92.2	236 530,-	184 580,-	20 850,-	7.45	222.5
		NG	42	86.5	228 050,-	176 490,-	23 947,-	7.03	208.8
	Floor heating system	Bio	*23	64.8	228 600,-	182 080,-	33 611,-	4.00	116.7
		El.	55	93.8	241 760,-	191 670,-	18 992,-	6.56	196.6
		NG	46	90.0	234 980,-	185 740,-	21 628,-	6.28	187.3
GSHP	High temperature radiator system	Bio	*23	73.4	223 990,-	177 330,-	33 746,-	5.46	158.7
		El.	39	94.3	236 920,-	184 900,-	20 923,-	7.96	237.0
		NG	33	89.1	229 960,-	178 370,-	23 984,-	7.68	227.6
	Low temperature radiator system	Bio	*23	74.7	228 970,-	183 580,-	32 373,-	5.06	147.1
		El.	40	95.8	237 090,-	187 050,-	18 942,-	7.04	210.5
		NG	34	91.3	231 250,-	181 900,-	21 736,-	6.91	205.4
	Floor heating system	Bio	*23	76.0	240 310,-	196 030,-	31 361,-	4.83	140.3
		El.	40	96.8	243 250,-	195 020,-	17 330,-	6.32	189.8
		NG	36	94.3	238 620,-	191 490,-	19 514,-	6.22	185.6

Table 24 shows the simulation results with horizontal PV system to counterbalance the CO_2-emissions, sorted by energy supply strategy. The differences in the results are not significant with regard to optimum HP power coverage factor (1-3% difference) or system solution. The main difference is that the area of needed PV goes up by about the same ratio as the electricity generation ratio for horizontal versus optimum sloped configuration. The increase in annual cost is due to the increase in PV area. However, for building with limited area for PV, this can be an option (ref. Section 2.3.10). As the results are similar to the ones for the optimum sloped PV, no further elaboration of these results are given.

Summary

The simulation results show, compared to the other two building standards simulated, that the ZEB office building have both different optimum HP power coverage factor and cost optimal energy supply strategy. The introduction of PV to counterbalance the CO_2-emissions alters the optimum design point but also seems to even out the annual total cost differences. There is however, not very big differences between the results from optimum sloped PV and horizontal PV, just a general increase in annual total cost for horizontal PV.

3.3 SENSITIVITY ANALYSIS

To check the sensitivity (i.e. robustness) of the results from Subchapter 3.2, the effect of some critical default values have been tested. The considered parameters are:

- Interest rate (TEK10 and ZEB)
- Nominal HP COP (TEK10 and ZEB)
- Peak power boiler efficiencies (TEK10 and ZEB)
- PV capital costs (ZEB)

The sensitivity analysis is only performed for the TEK10 and ZEB version of the office building for the first three parameters: interest rate, nominal HP COP and peak power boiler efficiencies. The passive office is discarded as this is an intermediate concept between the two others. For the PV capital costs, the sensitivity analysis will be done only for the ZEB version, as it is not an option for the TEK 10 level.

3.3.1 INTEREST RATE

The interest rate used in the annuity factor to find the annual capital cost for the installations, is considered to have a large impact on the ranking of the systems.

The interest rate was set to 7 % as default value, but what will happen to the ranking of the systems if the interest rate is increased or decreased? In the sensitivity analysis, two alternative interest rates are chosen: 9 % and 4 %.

TEK10 office building

Table 25 – The TEK10 office building, with the energy supply strategies sorted by annual total cost. The interest rate is set to 9% (all other input values are default).

Sorted by annual cost	*Characteristics for the different energy supply strategies in the TEK10 office building*								
	Energy supply strategy			Heat pump cover-age factor	Energy cover-age in percent (heating)	Total annual cost (incl DHW)	Annual investment cost (excl. DHW)	Annual operatio-nal cost (excl. DHW)	Annual CO_2 emission (tons)
	Heat pump tech-nology	Emission strategy	Peak power system	%	%	NOK/ year	NOK/ year	NOK/ year	t CO_2-/ year
1	ASHP	High temperature radiator system	El.	39	67.8	202 690,-	106 270,-	90 045,-	41.8
2	ASHP	Low temperature radiator system	El.	43	72.9	206 830,-	121 490,-	78 969,-	36.1
3	GSHP	High temperature radiator system	El.	26	59.3	215 550,-	112 300,-	96 877,-	46.0
4	ASHP	Floor heating system	El.	45	76.4	218 470,-	146 270,-	68 835,-	31.0
5	GSHP	Low temperature radiator system	El.	30	66.7	220 790,-	129 920,-	84 500,-	39.7
6	ASHP	High temperature radiator system	NG	52	78.8	224 520,-	123 150,-	94 359,-	31.5
7	ASHP	Low temperature radiator system	NG	53	80.6	227 390,-	136 160,-	84 223,-	27.3
8	GSHP	Floor heating system	El.	34	74.5	233 260,-	155 570,-	71 323,-	32.9
9	ASHP	Floor heating system	NG	55	83.5	237 440,-	157 940,-	72 494,-	22.9
10	GSHP	High temperature radiator system	NG	42	80.8	238 550,-	140 990,-	90 546,-	31.3
11	GSHP	Low temperature radiator system	NG	43	83.3	241 530,-	154 610,-	79 919,-	27.2
12	GSHP	Floor heating system	NG	44	86.4	251 600,-	176 240,-	68 348,-	23.0
13	ASHP	High temperature radiator system	Bio	40	68.8	307 300,-	194 580,-	106 320,-	20.9
14	ASHP	Low temperature radiator system	Bio	43	72.9	311 440,-	209 070,-	95 965,-	18.3
15	GSHP	High temperature radiator system	Bio	26	59.3	320 180,-	199 870,-	113 910,-	19.2
16	ASHP	Floor heating system	Bio	45	76.4	323 060,-	230 840,-	85 822,-	15.4
17	GSHP	Low temperature radiator system	Bio	30	66.7	325 410,-	217 500,-	101 510,-	17.8
18	GSHP	Floor heating system	Bio	34	74.5	337 860,-	243 140,-	88 316,-	16.1

Compared to Table 17 (i.e. 7% interest rate), Table 25 has generally lower HP power coverage factor. As the interest rate is higher, it is expected that high capital costs for the HPs will lead to lower power coverage factor. The energy coverage is therefore also lower. In addition, some disorder in the distinctive ranking pattern from before is seen, but nothing significant.

Table 26 – The TEK10 office building, with the energy supply strategies sorted by annual total cost. The interest rate is set to 4% (all other input values are default).

Sorted by annual cost	*Characteristics for the different energy supply strategies in the TEK10 office building*								
	Energy supply strategy			Heat pump cover-age factor	Energy cover-age in percent (heating)	Total annual cost (incl DHW)	Annual investment cost (excl. DHW)	Annual operatio-nal cost (excl. DHW)	Annual CO_2 emission (tons)
	Heat pump tech-nology	Emission strategy	Peak power system	%	%	NOK/ year	NOK/ year	NOK/ year	t CO_2-/ year
1	ASHP	Floorheating system	El.	53	82.3	161 070,-	91 109,-	63 863,-	28.0
2	ASHP	Low temperature radiator system	El.	50	78.6	162 820,-	82 028,-	74 685,-	33.6
3	ASHP	High temperature radiator system	El.	48	75.9	164 190,-	73 715,-	84 372,-	38.5
4	GSHP	Floorheating system	El.	45	87.4	166 180,-	100 820,-	59 258,-	26.3
5	GSHP	Low temperature radiator system	El.	44	84.3	167 940,-	92 447,-	69 390,-	31.3
6	GSHP	High temperature radiator system	El.	42	80.8	169 290,-	83 521,-	79 667,-	36.5
7	ASHP	Floorheating system	NG	63	87.6	175 950,-	101 650,-	67 579,-	22.0
8	GSHP	Floorheating system	NG	51	92.0	178 730,-	111 160,-	60 854,-	21.7
9	ASHP	Low temperature radiator system	NG	61	85.1	179 030,-	93 081,-	79 232,-	26.6
10	ASHP	High temperature radiator system	NG	60	83.6	181 430,-	85 277,-	89 431,-	31.0
11	GSHP	Low temperature radiator system	NG	51	90.1	181 750,-	103 610,-	71 430,-	25.9
12	GSHP	High temperature radiator system	NG	51	88.8	184 050,-	96 312,-	81 026,-	30.0
13	ASHP	Floorheating system	Bio	53	82.3	236 520,-	149 570,-	80 837,-	16.4
14	ASHP	Low temperature radiator system	Bio	50	78.6	238 270,-	140 480,-	91 668,-	19.4
15	ASHP	High temperature radiator system	Bio	48	75.9	239 650,-	132 170,-	101 360,-	22.6
16	GSHP	Floorheating system	Bio	45	87.4	241 610,-	159 270,-	76 220,-	17.9
17	GSHP	Low temperature radiator system	Bio	44	84.3	243 380,-	150 900,-	86 359,-	21.0
18	GSHP	High temperature radiator system	Bio	42	80.8	244 740,-	141 980,-	96 644,-	23.9

Compared to Table 17 (i.e. 7 %interest rate), Table 26 shows generally higher HP power coverage factor. As the interest rate is lower, it is expected that the strategies with high capital cost, but with better operation conditions, will perform better. As seen in the Table, the low operation cost of the low temperature heat emission systems are paying off and the floor heating and low temperature radiator systems are performing better. As the maintenance cost of the systems are linked to the capital cost, the operational cost of the GSHPs will never go below that of the ASHPs, and will therefore always perform worse. The ranking pattern is more distinct with regard to peak power technology.

Zero Emission office building

Table 27 – The ZEB office, with the energy supply strategies sorted by annual total cost. The interest rate is set to 9% (all other input values are default).

Sorted by annual cost	*Characteristics for the different energy supply strategies in the ZEB office building*									
	Energy supply strategy			Heat pump cover-age factor	Energy cover-age in percent (heating)	Total annual cost (incl. DHW)	Annual investment cost (excl. DHW)	Annual operatio-nal cost (excl. DHW)	Annual CO_2 emission (tons)	Area of photo-voltaic incl. DHW
	Heat pump tech-nology	Emission strategy	Peak power system	%	%	NOK/ year	NOK/ year	NOK/ year	t CO_2-/ year	m^2 PV
1	ASHP	High temperature radiator system	Bio	*23	62.7	229 300,-	180 880,-	35 464,-	4.57	110.6
2	ASHP	High temperature radiator system	NG	36	80.5	236 740,-	182 890,-	26 859,-	7.91	195.6
3	ASHP	Low temperature radiator system	Bio	*23	63.8	236 790,-	189 590,-	34 257,-	4.20	101.7
4	ASHP	Low temperature radiator system	NG	40	85.0	240 210,-	189 170,-	24 055	7.07	175.4
5	GSHP	High temperature radiator system	NG	31	86.7	241 570,-	190 190,-	24 391,-	7.75	191.7
6	GSHP	High temperature radiator system	Bio	*23	73.4	243 360,-	196 870,-	33 548,-	5.46	132.0
7	GSHP	Low temperature radiator system	NG	33	90.3	245 460,-	196 680,-	21 793,-	6.95	172.6
8	ASHP	High temperature radiator system	El.	46	88.1	246 570,-	193 470,-	22 763,-	8.68	215.4
9	ASHP	Low temperature radiator system	El.	50	90.9	248 380,-	197 741,-	20 633,-	7.58	188.9
10	GSHP	High temperature radiator system	El.	37	92.9	248 560,-	197 420,-	20 802,-	8.10	201.4
11	GSHP	Low temperature radiator system	Bio	*23	74.7	250 460,-	205 320,-	32 189,-	5.06	122.4
12	GSHP	Low temperature radiator system	El.	38	94.6	251 180,-	202 000,-	18 840,-	7.18	179.2
13	ASHP	Floor heating system	NG	43	88.2	252 920,-	204 080,-	21 846,-	6.37	158.5
14	ASHP	Floor heating system	Bio	*23	64.8	254 200,-	207 790,-	33 466,-	4.01	97.1
15	GSHP	Floor heating system	NG	34	92.6	258 600,-	211 760,-	19 843,-	6.33	157.5
16	ASHP	Floor heating system	El.	53	93.1	259 410,-	210 280,-	18 796,-	6.94	166.4
17	GSHP	Floor heating system	El.	39	96.2	263 210,-	215 690,-	17 182,-	6.39	160.4
18	GSHP	Floor heating system	Bio	*23	76.0	267 270,-	223 140,-	31 186,-	4.83	116.8

Compared to Table 23 (i.e. 7% interest rate), Table 27 shows generally higher annual cost. This is expected as the interest rate is higher. This increase in cost is mainly due to the annual capital cost, while the operational cost, CO_2-emission rate and PV area is more or less the same. The order of the ranking is also more or less the same, as well as the HP power and energy coverage (down by one percent for some of the energy supply strategies). The ranking is changed slightly, but not significantly.

Table 28 - The ZEB office, with the energy supply strategies sorted by annual total cost. The interest rate is set to 4% (all other input values are default).

Sorted by annual cost	Characteristics for the different energy supply strategies in the ZEB office building									
	Energy supply strategy			Heat pump cover-age factor	Energy cover-age in percent (heating)	Total annual cost (incl. DHW)	Annual investment cost (excl. DHW)	Annual operatio-nal cost (excl. DHW)	Annual CO_2 emission (tons)	Area of photo-voltaic incl. DHW
	Heat pump tech-nology	Emission strategy	Peak power system	%	%	NOK/ year	NOK/ year	NOK/ year	t CO_2-/ year	m² PV
1	ASHP	High temperature radiator system	Bio	*23	62,7	166310,-	119510,-	35 464,-	4,57	110,5
2	ASHP	High temperature radiator system	NG	38	82,4	168050,-	121310,-	26 402,-	7,87	192,8
3	GSHP	High temperature radiator system	NG	34	90,2	168590,-	124820,-	23414	7,64	187,3
4	ASHP	Low temperature radiator system	NG	42	86,5	168610,-	124580,-	23 692,-	7,03	172,5
5	GSHP	Low temperature radiator system	NG	35	92,2	169370,-	127820,-	21 210,-	6,87	168,7
6	ASHP	Low temperature radiator system	Bio	*23	63,8	170020,-	124420,-	34 257,-	4,20	101,5
7	ASHP	Floor heating system	NG	46	89,9	170380,-	128640,-	21 400,-	6,28	154,6
8	GSHP	High temperature radiator system	El.	39	94,3	170930,-	128110,-	20 634,-	7,96	195,6
9	GSHP	Low temperature radiator system	El.	39	95,2	171100,-	130150,-	18 755,-	7,10	175,2
10	GSHP	Floor heating system	NG	37	95,0	171380,-	131980,-	19 064,-	6,18	152,1
11	ASHP	Low temperature radiator system	El.	50	90,9	172100,-	129280,-	20 633,-	7,58	186,6
12	ASHP	High temperature radiator system	El.	46	88,1	172490,-	127530,-	22 763,-	8,68	213,0
13	GSHP	Floor heating system	El.	40	96,8	172550,-	133260,-	17 101,-	6,32	156,3
14	ASHP	Floor heating system	El.	53	93,1	172880,-	131900,-	18 796,-	6,94	164,1
15	GSHP	High temperature radiator system	Bio	*23	73,4	173820,-	128940,-	33 548,-	5,46	131,8
16	ASHP	Floor heating system	Bio	*23	64,8	175400,-	130590,-	33 466,-	4,01	97,0
17	GSHP	Low temperature radiator system	Bio	*23	74,7	177210,-	133680,-	32 189,-	5,06	122,2
18	GSHP	Floor heating system	Bio	*23	76,0	182130,-	139600,-	31 186,-	4,83	116,6

Compared to Table 23 (i.e. 7% interest rate), Table 28 shows generally lower annual cost. The gap between the most and least costly alternatives has also decreased. The decrease in cost is mainly due to the annual capital cost, while the operational cost, CO_2-emission rate and PV area are more or less the same. The HP power and energy coverage is close to the same for the given alternatives (up by one or two percent for some of the energy supply strategies). The ranking has changed, but the top and bottom of the list is more of less the same.

3.3.2 Nominal heat pump COP

The nominal COP for the HP used in the default values is an average based on a series of HP COPs from a project report (Løtveit, 2012), and are considered the same for the ASHP and the GSHP under nominal test conditions. In the sensitivity analysis the COP is changed to ± 1 from the initial 4.15 value.

TEK10 office building

Table 29 - The TEK10 office building, with the energy supply strategies sorted by annual total cost. The COP is set to a value of 5.15 (all other input values are default).

Sorted by annual cost	*Characteristics for the different energy supply strategies in the TEK10 office building*								
	Energy supply strategy			Heat pump cover-age factor	Energy cover-age in percent (heating)	Total annual cost (incl. DHW)	Annual investment cost (excl. DHW)	Annual operatio-nal cost (excl. DHW)	Annual CO_2 emission (tons)
	Heat pump tech-nology	Emission strategy	Peak power system	%	%	NOK/ year	NOK/ year	NOK/ year	t CO_2-/ year
1	ASHP	High temperature radiator system	El.	46	74.3	178 910,-	94 367,-	78 973,-	35.9
2	ASHP	Low temperature radiator system	El.	48	77.1	181 300,-	105 810,-	69 914,-	31.3
3	ASHP	Floor heating system	El.	50	80.3	188 150,-	122 030,-	60 555,-	26.6
4	GSHP	High temperature radiator system	El.	35	72.4	192 050,-	105 700,-	80 785,-	37.5
5	GSHP	Low temperature radiator system	El.	37	76.4	194 800,-	118 200,-	71 033,	32.6
6	ASHP	High temperature radiator system	NG	57	81.9	197 820,-	107 930,-	83 721,-	27.5
7	ASHP	Low temperature radiator system	NG	58	83.6	199 300,-	118 730,-	74 396,-	23.7
8	GSHP	Floor heating system	El.	40	82.2	201 840,-	136 630,-	59 636,-	26.8
9	ASHP	Floor heating system	NG	59	85.7	204 910,-	134 310,-	64 432,-	19.7
10	GSHP	High temperature radiator system	NG	46	84.8	210 430,-	125 040,-	79 216,-	27.4
11	GSHP	Low temperature radiator system	NG	46	86.2	211 920,-	135 200,-	70 539,-	23.8
12	GSHP	Floor heating system	NG	47	89.0	217 430,-	154 310,-	59 949,-	20.0
13	ASHP	High temperature radiator system	Bio	46	74.3	271 180,-	169 650,-	95 966,-	19.0
14	ASHP	Low temperature radiator system	Bio	48	77.1	273 560,-	181 090,-	86 900,-	16.2
15	ASHP	Floor heating system	Bio	50	80.3	280 410,-	197 310,-	77 533,-	13.6
16	GSHP	High temperature radiator system	Bio	35	72.4	284 330,-	180 980,-	97 783,-	19.3
17	GSHP	Low temperature radiator system	Bio	37	76.4	287 070,-	193 480,-	88 021,-	17.0
18	GSHP	Floor heating system	Bio	40	82.2	294 090,-	211 910,-	76 610,-	15.0

Compared to Table 17 (i.e. 4.15 COP), Table 29 shows generally higher HP power coverage factor. As the COP is higher, the significantly lower operational cost of the HP, an incentive for higher energy coverage and thus higher power coverage factor is given by some few percentage points. Also the CO_2-emissions have declined, as less electricity is needed to operate the HP, due to higher COP. However, the order of the ranking is not affected to any significant degree.

Table 30 - The TEK10 office building, with the energy supply strategies sorted by annual total cost. The COP is set to a value of 3.15 (all other input values are default).

Sorted by annual cost	*Characteristics for the different energy supply strategies in the TEK10 office building*								
	Energy supply strategy			Heat pump coverage factor	Energy coverage in percent (heating)	Total annual cost (incl. DHW)	Annual investment cost (excl. DHW)	Annual operational cost (excl. DHW)	Annual CO_2 emission (tons)
	Heat pump technology	Emission strategy	Peak power system	%	%	NOK/ year	NOK/ year	NOK/ year	t CO_2-/ year
1	ASHP	High temperature radiator system	El.	35	63.5	197 950,-	88 891,-	101 920,-	48.0
2	ASHP	Low temperature radiator system	El.	41	71.0	199 160,-	102 900,-	89 110,-	41.3
3	ASHP	Floorheating system	El.	45	76.4	204 060,-	120 400,-	76 508,-	34.8
4	GSHP	High temperature radiator system	El.	28	62.4	204 370,-	95 527,-	101 700,-	48.3
5	GSHP	Low temperature radiator system	El.	34	72.4	206 160,-	111 920,-	87 089,-	40.7
6	GSHP	Floorheating system	El.	38	79.8	211 370,-	131 010,-	73 212,-	33.6
7	ASHP	Low temperature radiator system	NG	53	80.6	219 770,-	117 400,-	94 331,-	32.3
8	ASHP	High temperature radiator system	NG	51	78.1	220 370,-	105 950,-	106 380,-	37.1
9	ASHP	Floorheating system	NG	56	84.1	222 670,-	134 250,-	80 370,-	27.0
10	GSHP	Low temperature radiator system	NG	46	86.2	224 830,-	131 180,-	85 604,-	31.3
11	GSHP	High temperature radiator system	NG	44	82.9	225 380,-	118 940,-	98 398,-	36.1
12	GSHP	Floorheating system	NG	47	89.1	227 750,-	147 160,-	72 552,-	26.2
13	ASHP	High temperature radiator system	Bio	35	63.5	290 690,-	164 390,-	118 930,-	23.9
14	ASHP	Low temperature radiator system	Bio	41	71.0	291 870,-	178 400,-	106 110,-	22.1
15	ASHP	Floorheating system	Bio	45	76.4	296 760,-	195 900,-	93 496,-	19.2
16	GSHP	High temperature radiator system	Bio	29	64.0	297 100,-	172 060,-	117 680,-	24.0
17	GSHP	Low temperature radiator system	Bio	34	72.4	298 870,-	187 420,-	104 090,-	22.6
18	GSHP	Floorheating system	Bio	38	79.8	304 060,-	206 510,-	90 192,-	20.3

Compared to Table 17 (i.e. 4.15 COP), Table 30 shows generally lower HP power coverage factor. As the COP is lower, higher operational costs of the HP incentive lower energy coverage and thus lower power coverage factor but only by some few percentage points. Also the CO_2-emissions have increased. However, the order of the ranking is not affected at all.

Zero Emission office building

Table 31 - The ZEB office, with the energy supply strategies sorted by annual total cost. The COP is set to a value of 5.15 (all other input values are default).

Sorted by annual cost	Characteristics for the different energy supply strategies in the ZEB office building									
	Energy supply strategy			Heat pump cover-age factor	Energy cover-age in percent (heating)	Total annual cost (incl. DHW)	Annual investment cost (excl. DHW)	Annual operatio-nal cost (excl. DHW)	Annual CO2 emission (tons)	Area of photo-voltaic incl. DHW
	Heat pump tech-nology	Emission strategy	Peak power system	%	%	NOK/ year	NOK/ year	NOK/ year	t CO_2-/ year	m^2 PV
1	ASHP	High temperature radiator system	NG	41	84.8	191 680,-	146 840,-	23 450,-	6.74	166.2
2	ASHP	High temperature radiator system	Bio	*23	62.7	194 420,-	148 820,-	33 854,-	3.84	93.1
3	ASHP	Low temperature radiator system	NG	44	87.8	194 870,-	152 260,-	21 223,-	6.00	148.5
4	GSHP	High temperature radiator system	NG	34	90.2	196 810,-	154 150,-	21 275,-	6.67	164.6
5	ASHP	High temperature radiator system	El.	51	90.6	196 870,-	153 330,-	20 033,-	7.17	179.8
6	ASHP	Low temperature radiator system	El.	53	92.2	199 060,-	157 300,-	18 246,-	6.40	158.7
7	GSHP	High temperature radiator system	El.	39	94.3	200 000,-	158 130,-	18 354,-	6.92	171.3
8	GSHP	Low temperature radiator system	NG	35	92.2	200 440,-	159 730,-	19 326,-	6.01	148.7
9	ASHP	Low temperature radiator system	Bio	*23	63.8	201 070,-	156 520,-	32 819,-	3.55	86.1
10	GSHP	Low temperature radiator system	El.	39	95.2	202 940,-	162 640,-	16 788,-	6.21	154.3
11	ASHP	Floor heating system	NG	47	90.4	204 140,-	163 370,-	19 384,-	5.40	134.0
12	GSHP	High temperature radiator system	Bio	*23	73.4	206 280,-	162 630,-	31 914,-	4.72	114.2
13	ASHP	Floor heating system	El.	55	93.9	207 280,-	167 000,-	16 772,-	5.66	141.0
14	GSHP	Floor heating system	NG	36	94.3	210 080,-	171 010,-	17 678,-	5.49	136.2
15	GSHP	Floor heating system	El.	39	96.2	211 910,-	172 870,-	15 531,-	5.64	140.6
16	GSHP	Low temperature radiator system	Bio	*23	74.7	212 630,-	170 150,-	30 742,-	4.40	106.6
17	ASHP	Floor heating system	Bio	*23	64.8	214 200,-	170 270,-	32 202,-	3.44	83.4
18	GSHP	Floor heating system	Bio	*23	76.0	225 280,-	183 620,-	29 927,-	4.26	103.1

Compared to Table 23 (i.e. 4.15 COP), Table 31 shows generally lower CO_2-emissions, due to the improved COP, and also generally slightly higher HP power and energy coverage factor. The low CO_2-emissions call for less PV, and relatively more for the most CO_2-intensive combinations. This has led to a change in the top ranking, bringing the ASHP with high temperature radiator system and natural gas boiler to the top of the list. Also some other changes can be found in the order of the ranking, but nothing significant.

Table 32 - The ZEB office, with the energy supply strategies sorted by annual total cost. The COP is set to a value of 3.15 (all other input values are default).

Sorted by annual cost	Characteristics for the different energy supply strategies in the ZEB office building									
	Energy supply strategy			Heat pump cover-age factor	Energy cover-age in percent (heating)	Total annual cost (incl. DHW)	Annual investment cost (excl. DHW)	Annual operatio-nal cost (excl. DHW)	Annual CO_2 emission (tons)	Area of photo-voltaic incl. DHW
	Heat pump tech-nology	Emission strategy	Peak power system	%	%	NOK/ year	NOK/ year	NOK/ year	t CO_2-/ year	m^2 PV
1	ASHP	High temperature radiator system	Bio	*23	62.7	215 710,-	164 720,-	38 095,-	5.77	139.1
2	ASHP	Low temperature radiator system	Bio	*23	63.8	220 340,-	170 840,-	36 607,-	5,27	127,1
3	GSHP	High temperature radiator system	Bio	*23	73,4	226 130,-	177 010,-	36 220,-	6.67	160.9
4	ASHP	High temperature radiator system	NG	29	72.3	229 780,-	170 040,-	32 288,-	9.57	235.1
5	GSHP	Low temperature radiator system	Bio	*23	74.7	230 280,-	182 830,-	34 556,-	6.14	148.0
6	GSHP	High temperature radiator system	NG	28	82.4	230 430,-	174 180,-	28 803,-	9.31	228.8
7	ASHP	Low temperature radiator system	NG	35	80.6	231 190,-	175 310,-	28 427,-	8.68	213.4
8	ASHP	Floor heating system	Bio	*23	64.8	231 410,-	182 990,-	35 531,-	4.95	119.5
9	GSHP	Low temperature radiator system	NG	31	88.0	231 660,-	178 790,-	25 415,-	8.37	206.4
10	ASHP	Floor heating system	NG	40	86.1	237 850,-	185 070,-	25 328,-	7.79	192.3
11	GSHP	Floor heating system	NG	34	92.6	238 360,-	188 490,-	22421	5.49	136.2
12	GSHP	Low temperature radiator system	El.	37	93.9	239 510,-	185 680,-	22 098,-	8.69	215.7
13	GSHP	High temperature radiator system	El.	36	92.1	240 010,-	183 770,-	24 512,-	9.82	242.8
14	GSHP	Floor heating system	Bio	*23	76.0	240 710,-	194 570,-	33 244,-	5.76	139.0
15	ASHP	Low temperature radiator system	El.	44	87.8	242 150,-	185 980,-	24 436,-	9.51	235.4
16	ASHP	High temperature radiator system	El.	41	84.8	243 090,-	184 410,-	26 944,-	10.75	265.2
17	GSHP	Floor heating system	El.	38	95.7	244 880,-	193 190,-	19 958,-	7.68	191.6
18	ASHP	Floor heating system	El.	50	91.9	246 780,-	192 990,-	22 055,-	8.22	204.6

Compared to Table 23 (i.e. 4.15 COP), Table 32 shows generally higher CO_2-emissions, due to the lower COP, and also generally slightly lower HP power and energy coverage factor. The high CO_2-emissions call for more PV (so much that almost half are in over the threshold limit of 1/3, ref. Section 2.3.10), and the peak power systems with low CO_2-emissions perform better. The top three on the ranking are all bio-boiler peak power energy supply strategies, and the electric boiler peak power systems are all found on the bottom of the list, a drastic change.

3.3.3 PEAK POWER BOILER EFFICIENCIES

The peak power boiler efficiencies used as default can in reality vary between suppliers and models. To see if the results will change when these efficiencies are altered, a sensitivity analysis is performed. The efficiencies are in the default input list set to the SIMIEN default values. Here they are changed to:

Table 33 – Table showing the initial default input peak power boiler efficiencies and the ones used in the sensitivity analysis.

Boiler type	Default value	Value used in sensitivity analysis
Bio-boiler	0.73	0.80
Electric boiler	0.90	0.95
Natural Gas boiler	0.80	0.90

TEK10 office building

Table 34 - The TEK10 office building, with the energy supply strategies sorted by annual total cost. The peak power boiler efficiencies are altered (all other input values are default).

Sorted by annual cost	*Characteristics for the different energy supply strategies in the TEK10 office building*								
	Energy supply strategy			Heat pump cover-age factor	Energy cover-age in percent (heating)	Total annual cost (incl. DHW)	Annual investment cost (excl. DHW)	Annual operatio-nal cost (excl. DHW)	Annual CO_2 emission (tons)
	Heat pump tech-nology	Emission strategy	Peak power system	%	%	NOK/ year	NOK/ year	NOK/ year	t CO_2-/ year
1	ASHP	High temperature radiator system	El.	40	68.8	184 240,-	91 088,-	87 019,-	40.3
2	ASHP	Low temperature radiator system	El.	43	72.9	186 290,-	103 180,-	76 987,-	35.1
3	ASHP	Floorheating system	El.	46	77.2	192 610,-	120 030,-	66 438,-	29.7
4	GSHP	High temperature radiator system	El.	29	63.9	194 370,-	97 860,-	90 370,-	42.6
5	GSHP	Low temperature radiator system	El.	33	71.1	197 160,-	112 500,-	78 527,-	36.5
6	ASHP	High temperature radiator system	NG	50	77.4	201 700,-	103 880,-	91 201,-	30.6
7	ASHP	Low temperature radiator system	NG	52	79.9	202 780,-	115 330,-	80 837,-	26.5
8	GSHP	Floorheating system	El.	37	78.5	203 930,-	131 900,-	65 891,-	30.0
9	ASHP	Floorheating system	NG	54	82.9	207 880,-	131 540,-	69 715 t	22.2
10	GSHP	High temperature radiator system	NG	41	79.7	211 960,-	117 660,-	87 685,-	30.5
11	GSHP	Low temperature radiator system	NG	43	83.3	213 130,-	130 060,-	76 459,-	26.4
12	GSHP	Floorheating system	NG	44	86.4	218 260,-	146 110,-	65 537,-	22.4
13	ASHP	High temperature radiator system	Bio	38	66.7	274 940,-	165 070,-	103 750,-	20.3
14	ASHP	Low temperature radiator system	Bio	42	71.9	277 200,-	177 800,-	93 276,-	18.0
15	ASHP	Floorheating system	Bio	45	76.4	283 710,-	194 660,-	82 936,-	15.4
16	GSHP	High temperature radiator system	Bio	27	60.9	284 800,-	170 890,-	107 790,-	19.5
17	GSHP	Low temperature radiator system	Bio	31	68.2	287 950,-	185 520,-	96 302,-	17.9
18	GSHP	Floorheating system	Bio	36	77.2	295 080,-	206 050,-	82 906,-	16.4

Compared to Table 17 (i.e. default peak power boiler efficiencies), the values in Table 34 are not so different. As the peak power boiler efficiencies are increased, it is as expected that the HP power coverage factors decreases. However, is has not gone down by more than some few percentage points. The changes has just altered the ranking slightly.

Zero Emission office building

Table 35 - The ZEB office building, with the energy supply strategies sorted by annual total cost. The peak power boiler efficiencies are altered (all other input values are default).

Sorted by annual cost	*Characteristics for the different energy supply strategies in the ZEB office building*									
	Energy supply strategy			Heat pump cover-age factor	Energy cover-age in percent (heating)	Total annual cost (incl. DHW)	Annual investment cost (excl. DHW)	Annual operatio-nal cost (excl. DHW)	Annual CO_2 emission (tons)	Area of photo-voltaic incl. DHW
	Heat pump tech-nology	Emission strategy	Peak power system	%	%	NOK/ year	NOK/ year	NOK/ year	t CO_2-/ year	m^2 PV
1	ASHP	High temperature radiator system	Bio	*23	62.7	199 720,-	153 990,-	34 215,-	4.54	109.8
2	ASHP	High temperature radiator system	NG	33	77.4	201 900,-	152 690,-	26 357,-	7.71	189.5
3	ASHP	Low temperature radiator system	NG	37	82.5	204 850,-	158 290,-	23 700,-	6.94	171.2
4	ASHP	Low temperature radiator system	Bio	*23	63.8	205 640,-	161 090,-	33 044,-	4.17	100.9
5	GSHP	High temperature radiator system	NG	29	84.0	205 950,-	158 810,-	24 284,-	7.65	188.0
6	GSHP	Low temperature radiator system	NG	31	88.0	209 090,-	164 420,-	21 811,-	6.91	170.4
7	GSHP	High temperature radiator system	Bio	*23	73.4	211 440,-	167 280,-	32 656,-	5.44	131.4
8	ASHP	High temperature radiator system	El.	45	87.5	213 200,-	164 230,-	22 524,-	8.61	212.5
9	ASHP	Floor heating system	NG	41	86.8	213 540,-	169 240,-	21 446,-	6.27	155.1
10	GSHP	High temperature radiator system	El.	37	92.9	214 230,-	167 130,-	20 647,-	8.03	198.6
11	ASHP	Low temperature radiator system	El.	48	90.0	214 330,-	167 410,-	20 478,-	7.58	187.8
12	GSHP	Low temperature radiator system	El.	38	94.6	215 950,-	170 780,-	18 722,-	7.12	176.9
13	GSHP	Low temperature radiator system	Bio	*23	74.7	217 010,-	174 160,-	31 341,-	5.04	121.8
14	ASHP	Floor heating system	Bio	*23	64.8	218 030,-	174 240,-	32 287,-	3.98	96.4
15	GSHP	Floor heating system	NG	33	91.6	218 030,-	175 500,-	19 676,-	6.28	155.2
16	ASHP	Floor heating system	El.	52	92.7	221 290,-	176 170,-	18 667,-	6.62	164.8
17	GSHP	Floor heating system	El.	38	95.7	223 670,-	180 040,-	17 184,-	6.43	160.1
18	GSHP	Floor heating system	Bio	*23	76.0	228 870,-	186 980,-	30 383,-	4.81	116.2

Compared to Table 23 (default peak power boiler efficiencies), Table 35 is not so different. As the peak power boiler efficiencies are turned up, it is expected that the HP power coverage factors has gone down; however, they have not gone down by more than some few percentage points, and thus also a decrease in HP energy coverage is seen. The CO_2-emissions has also gone down a little, and thus also the PV area. The increased peak power boiler efficiencies have not altered the ranking order significantly. The reason for the moderate changes might be due to the little change in peak power boiler efficiencies.

3.3.4 COST OF PHOTOVOLTAIC PANEL

The cost of the PV panel is also found in “Information database for support in decision making on ZEB energy system in early design stage” (Løtveit, 2012). As the PV industry is in rapid development, the cost has a large uncertainty attached to it. To see how much the cost of PV impacts the results of the simulations, the sensitivity to PV cost is checked. The cost is varied with ± 50 % of the initial cost.

Zero Emission office building

Table 36 - The ZEB office, with the energy supply strategies sorted by annual total cost. The PV capital costs are 37 500 NOK/kWp (all other input values are default).

Sorted by annual cost	*Characteristics for the different energy supply strategies in the ZEB office building*									
	Energy supply strategy			Heat pump cover-age factor	Energy cover-age in percent (heating)	Total annual cost (incl. DHW)	Annual investment cost (excl. DHW)	Annual operatio-nal cost (excl. DHW)	Annual CO_2 emission (tons)	Area of photo-voltaic incl. DHW
	Heat pump tech-nology	Emission strategy	Peak power system	%	%	NOK/ year	NOK/ year	NOK/ year	t CO_2-/ year	m^2 PV
1	ASHP	High temperature radiator system	Bio	*23	62.7	223060,-	173880,-	35 464,-	4.57	110.4
2	ASHP	Low temperature radiator system	Bio	*23	63.8	227520,-	179550,-	34 257,-	4.20	101.5
3	GSHP	High temperature radiator system	Bio	*23	73.4	237780,-	190520,-	33 548,-	5.46	131.8
4	ASHP	Floor heating system	Bio	*23	64.8	239150,-	191970,-	33 466,-	4.01	96.9
5	GSHP	Low temperature radiator system	Bio	*23	74.7	241770,-	195860,-	32 189,-	5.06	122.1
6	GSHP	Floor heating system	Bio	*23	76.0	252680,-	207780,-	31 186,-	4.83	116.5
7	ASHP	High temperature radiator system	NG	39	83.3	254660,-	195880,-	26 203,-	7.86	193.4
8	GSHP	Low temperature radiator system	NG	36	93.1	256500,-	202960,-	20 964,-	6.83	168.8
9	ASHP	Low temperature radiator system	NG	43	87.2	256650,-	197530,-	23 534,-	7.01	173.0
10	GSHP	High temperature radiator system	NG	34	90.2	257020,-	201030,-	23 414,-	7.64	188.3
11	ASHP	Floor heating system	NG	48	90.9	258840,-	205120,-	21 148,-	6.23	154.4
12	GSHP	Floor heating system	NG	37	95.0	262370,-	210730,-	16 064,-	6.18	153.2
13	GSHP	Low temperature radiator system	El.	42	96.8	264950,-	209150,-	18 588,-	6.92	172.2
14	ASHP	Low temperature radiator system	El.	56	93.4	265290,-	207500,-	20 571,-	7.35	182.3
15	GSHP	High temperature radiator system	El.	41	95.5	266810,-	209070,-	20 532,-	7.84	194.2
16	ASHP	Floor heating system	El.	57	94.5	268500,-	212540,-	18 739,-	6.48	161.5
17	ASHP	High temperature radiator system	El.	52	91.1	268590,-	208680,-	22 692,-	8.45	208.7
18	GSHP	Floor heating system	El.	42	97.6	269660,-	215450,-	16 996,-	6.20	154.9

Compared to Table 23 (i.e. 25 000 NOK/kWp), Table 36 has much more distinct ranking pattern. As the cost of PV is increased, the combinations applying low CO_2-emissions peak power systems perform best. All the bio-boiler energy supply strategy solutions have moved to the top of the list, as these calls for least CO_2-emissions counterbalancing. It is followed by natural gas boilers and electric boilers are at the bottom. However, neither the HP power coverage factor nor the PV area has changed much, only the total annual cost has. The reason for the moderate changes might be due to the little change in peak power boiler efficiencies.

Table 37 - The ZEB office, with the energy supply strategies sorted by annual total cost. The PV capital costs are 12 500 NOK/kWp (all other input values are default).

Sorted by annual cost	*Characteristics for the different energy supply strategies in the ZEB office building*									
	Energy supply strategy			Heat pump cover-age factor	Energy cover-age in percent (heating)	Total annual cost (incl. DHW)	Annual investment cost (excl. DHW)	Annual operatio-nal cost (excl. DHW)	Annual CO_2 emission (tons)	Area of photo-voltaic incl. DHW
	Heat pump tech-nology	Emission strategy	Peak power system	%	%	NOK/ year	NOK/ year	NOK/ year	t CO_2-/ year	m^2 PV
1	ASHP	High temperature radiator system	NG	34	78.5	160 530,-	117430,-	27 388,-	7.96	196.1
2	ASHP	High temperature radiator system	El.	40	84,1	160 910,-	121 220,-	16 091,-	9,04	222.9
3	GSHP	High temperature radiator system	El.	33	89.1	163 660,-	125 710,-	21 360,-	8.49	209.8
4	GSHP	High temperature radiator system	NG	29	84.0	164 150,-	123 200,-	25 226,-	7.85	193.3
5	ASHP	Low temperature radiator system	El.	42	86.5	165 730,-	128 090,-	21 044,-	8.04	199.0
6	GSHP	Low temperature radiator system	El.	34	91.3	168 730,-	132 750,-	19 387,-	7.56	187.5
7	ASHP	Low temperature radiator system	NG	37	82.5	168 880,-	125 440,-	24 727,-	7.16	176.9
8	GSHP	Low temperature radiator system	NG	31	88.0	169 670,-	131 440,-	22 518,-	7.06	174.4
9	ASHP	Floor heating system	El.	44	88.8	176 040,-	140 150,-	19 299,-	7.18	178.3
10	ASHP	Floor heating system	NG	40	86.1	176 680,-	138 530,-	22 434,-	6.47	160.4
11	GSHP	Floor heating system	El.	35	93.5	179 220,-	144 930,-	17 698,-	6.76	168.3
12	GSHP	Floor heating system	NG	32	90.5	180 610,-	144 350,-	20 539,-	6.45	159.8
13	ASHP	High temperature radiator system	Bio	*23	62.7	181 410,-	135 570,	35 464,-	4.57	111.1
14	ASHP	Low temperature radiator system	Bio	*23	63.8	188 720,-	144 090,-	34 257,-	4.20	102.2
15	GSHP	High temperature radiator system	Bio	*23	73.4	189 310,-	145 400,-	33 548,-	5.46	132.5
16	GSHP	Low temperature radiator system	Bio	*23	74.7	196 360,-	153 810,-	32 189,-	5.06	122.8
17	ASHP	Floor heating system	Bio	*23	64.8	201 790,-	157 960,-	33 466,-	4.01	97.6
18	GSHP	Floor heating system	Bio	*23	76.0	209 060,-	167 510,-	31 186,-	4.83	117.2

Compared to Table 23 (25 000 NOK/kWp), Table 37 is quite different. The optimum HP power coverage factor has gone down, as well as energy coverage, while CO_2-emissions have generally gone up. The exceptions are the bio-boiler peak power systems (which has the optimum given by the cooling power). The results are approaching those seen for the passive office building (ref. Table 20). As the cost of the PV is low, this makes sense.

3.4 SIMULATIONS WITH NIGHT SET-BACK

The idea with night setback is to save energy on the annual basis. However, to have the building heated up again after lower temperature during night, higher peak powers are needed. As stated earlier (ref. 3.2, “Simulation results”), night setback is an inappropriate operation strategy for buildings using the HP technology. This is from a “HP operational”-point of view, where the HP has poor operational conditions at the start-up (Smedegård, 2013). However, in the following Subchapter, the TEK10 and ZEB office building is simulated using power requirements and SIMIEN “Annual simulation”-file with night setback settings to see if it would be beneficial from an economic point of view. Other than the SIMIEN-file being obtained using simulation with night setback, the other settings are the default-values used earlier.

3.4.1 TEK10 OFFICE BUILDING

Table 38 – The building specific input used in the Beta-version simulation tool for the TEK10 office building with night setback settings. As described, there is no room load cooling. The design conditions for heating are without internal loads or solar gain (net power).

TEK10 office building with «night setback»		
Design power for room heating	120.3	kW
Design power for ventilation heating	41.2	kW
Energy use for DHW	12000	kWh
Building size	2394.2	m2
Design power for room cooling	0	kW
Design power for ventilation cooling	19.2	kW
Energy recovery unit efficiency	0.8	-

As seen, compared to the power requirements in Table 15, the heating power requirements are significantly higher with the night setback settings (Table 38).

Table 39 – The HP energy and power coverage factor (heating mode only) for the TEK10 office building with night setback settings. Total annual cost is the sum of annual capital cost and operational cost, including DHW. Annual capital cost and operational cost given as explained in Section 2.3.11 (excl. DHW). All prices are in NOK. The cheapest energy supply strategy on an annual basis is marked in green.

Characteristics for the different energy supply strategies in the TEK10 office building with "night setback"								
Energy supply strategy			HP cover-age factor	Energy cover-age in percent (heating)	Total annual cost (incl. DHW)	Annual capital cost (excl. DHW)	Annual operatio-nal cost (excl. DHW)	Annual CO_2 emission (tons)
HP technology	Emission strategy	Peak power system	%	%	NOK/ year	NOK/ year	NOK/ year	t CO_2-/ year
ASHP	High temperature radiator system	Bio	22	67.4	302 970,-	203 640,-	93 053,-	13.2
		El.	22	67.4	164 340,-	90 526,-	67 552,-	31.1
		NG	29	77.6	187 530,-	106 760,-	73 889,-	22.7
	Low temperature radiator system	Bio	24	71.5	310 100,-	215 880,-	87 940,-	12.8
		El.	24	71.5	171 470,-	102 760,-	62 447,-	28.3
		NG	31	80.6	193 510,-	119 000,-	67 624,-	20.7
	Floor heating system	Bio	26	75.8	321 850,-	232 880,-	82 686,-	12.3
		El.	26	75.8	183 230,-	119 770,-	57 202,-	25.6
		NG	32	82.8	204 040,-	135 040,-	62 117,-	18.8
GSHP	High temperature radiator system	Bio	16	64.2	310 540,-	209 320,-	94 940,-	12.9
		El.	16	64.2	171 900,-	96 206,-	69 433,-	32.6
		NG	23	79.2	195 340,-	117 450,-	71 001,-	22.5
	Low temperature radiator system	Bio	18	69.9	318 170,-	222 990,-	88 905,-	12.9
		El.	18	69.9	179 540,-	109 880,-	63 409,-	29.4
		NG	24	81.9	201 490,-	129 440,-	65 162,-	20.7
	Floor heating system	Bio	20	75.9	330 600,-	241 430,-	82 895,-	13.0
		El.	20	75.9	191 990,-	128 320,-	57 410,-	26.2
		NG	25	85.0	212 270,-	146 200,-	59 181,-	18.9

The HP power coverage factor should not be compared with Table 16, as the design conditions have changed. It is better to compare energy coverage instead (but not optimal). Compared to Table 16, the operational cost and CO_2-emissions have been drastically decreased for all combinations, and thus the required PV area. For the electric and natural gas boiler systems, the annual has been reduced (about 10-15%). However, for the combinations with the relatively costly bio-boiler peak power technology, the annual cost has increased relatively much (about 10%). From an economic point of view, with the boundaries used in this calculation, it seems that it is beneficial to have night setback for the system with "cheap" peak power systems, while for combinations with "expensive" peak power system it is not beneficial.

3.4.2 ZERO EMISSION OFFICE BUILDING

Table 40 – The building specific input used in the Beta-version simulation tool for the Zero Emission office Building with night setback setting. As described, there is no room cooling. The design conditions for heating are without internal loads or solar gain (net power).

ZEB office building without «night setback»		
Design power for room heating	84.2	kW
Design power for ventilation heating	26.6	kW
Energy use for DHW	12000	kWh
Building size	2394.2	m2
Design power for room cooling	0	kW
Design power for ventilation cooling	14.4	kW
Energy recovery unit efficiency	0.85	-

As seen, compared to the power requirements in Table 21, the heating power requirements are significantly higher for the night setback setting.

Table 41 –The HP energy and power coverage factor (heating mode only) for the ZEB office building with night setback settings. Total annual cost is the sum of annual capital cost and operational cost, including DHW. Annual capital cost and operational cost given as explained in Section 2.3.11 (excl. DHW). The cheapest energy supply strategy on an annual basis is marked in green.

Characteristics for the different energy supply strategies in the ZEB office building										
Energy supply strategy			HP cover-age factor	Energy cover-age in percent (heating)	Total annual cost (incl. DHW)	Annual capital cost (excl. DHW)	Annual operatio-nal cost (excl. DHW)	Annual CO_2 emission (tons)	Area of photo-voltaic incl. DHW
HP technology	Emission strategy	Peak power system	%	%	NOK/ year	NOK/ year	NOK/ year	t CO_2-/ year	m^2 PV
ASHP	High temperature radiator system	Bio	*13	58.6	237 190,-	184 910,-	39 982,-	3.66	88.8
		El.	26	81.3	210 670,-	162 700,-	21 074,-	7.87	194.9
		NG	19	71.3	204 670,-	153 930,-	26 536,-	6.89	170.2
	Low temperature radiator system	Bio	*13	59.3	243 930,-	192 550,-	39 081,-	3.34	81.2
		El.	29	85.0	213 670,-	167 410,-	19 356,-	6.91	171.8
		NG	22	76.9	209 190,-	160 840,-	24 158,-	6.21	154.0
	Floor heating system	Bio	*13	60.1	256 550,-	205 820,-	38 427,-	3.15	76.6
		El.	30	86.7	221 860,-	177 100,-	17 849,-	6.16	154.0
		NG	25	81.8	218 670,-	172 490,-	21 978,-	5.55	138.1
GSHP	High temperature radiator system	Bio	*13	67.6	247 630,-	169 530,-	38 797,-	4.35	105.2
		El.	20	83.2	214 440,-	167 550,-	19 987,-	7.74	191.7
		NG	15	72.9	209 400,-	159 350,-	25 844,-	6.98	172.3
	Low temperature radiator system	Bio	*13	68.4	254 250,-	204 120,-	37 824,-	4.02	97.4
		El.	21	85.5	218 270,-	172 930,-	18 434,-	6.97	173.4
		NG	17	78.5	214 480,-	166 860,-	23 421,-	6.34	157.1
	Floor heating system	Bio	*13	69.4	266 690,-	217 300,-	37 086,-	3.82	92.6
		El.	22	87.7	227 540,-	183 580,-	17 059,-	6.29	156.9
		NG	19	83.5	224 710,-	179 300,-	21 208,-	5.74	142.7

Compared to Table 22, the operational cost and CO_2-emissions have been decreased, as well as the required PV area for all the installations have gone down. For the electric and natural gas boiler systems, the annual cost in almost the same as before with, only some small deviations are found. However, for the combinations with the relatively costly bio-boiler peak power technology has had a large increase in annual cost. All in all, there is little or nothing to save from an economic point of view, with the boundaries used in this calculation. The HP power coverage factor should not be compared as the "100 %-mark" has moved, and it is better to compare energy coverage instead (better, but not optimal).

4. CONCLUSION

As the Beta-version simulation tool have some delimitations, simplifications and assumptions regarding the calculations and default values, the results have limited scientific value. However, for the purpose as a proof of concept, the results and findings are highly interesting.

In Section 2.1, “Why a simulation tool?”, a short list of “rules of thumbs” are presented. The list is based on earlier HP research and experiences, and is often used by the consultant business when designing HP systems. In Chapter 3, a benchmark office building is introduced and the Beta-version simulation tool is tested. The results show that the simulation tool gives output according to theory for the TEK10 office building, where the “rules of thumb are expected to apply. The HP power coverage factor and energy coverage are roughly as expected, as well as the shapes of the cost optimization curves.

When it comes to the annual cost of energy supply strategies and their ranking (based on annual cost and CO_2-emissions), there are larger uncertainties. However, as expected the peak power system with lowest installation cost were top-ranked for the TEK10 office. On the other hand, the GSHPs do not perform as well as expected. This may be due to disproportionately high maintenance cost (due to borehole cost added to HP capital cost, here) or because the ratio between GSHP and ASHP COP is favorable to ASHP. It could also be due to the fact that an outdoor temperature limit is not implemented for the ASHP, giving it unrealistically high energy coverage. The exact reason why it performs worse than expected is not found, but the sum unfavorable factor probably adds up to the bad performance. However, the Beta-version simulation tool is considered sufficient to determine the best energy supply strategy, with an acceptable degree of uncertainty.

The building envelope design and characteristics are considered the same for the ZEB and passive office. The results for the ZEB and passive office buildings have no available “rules of thump”. However, some indications and expectations are found. It was expected that a certain HP power coverage factor would give higher energy coverage factor compared to the TEK10 office, something that is found in the results (the reason for this is explained in Figure 23). The passive office has similar results as the TEK10 office, only significantly lower operational costs. This is expected, as the building envelope is significantly more energy efficient.

On the other hand, the ZEB office must counterbalance CO_2-emsisions. Emissions related to the operation of the HVAC and DWH systems taken into account. The results are then different than for the two other building concepts. The less CO_2-intensive and high cost peak power systems perform better (i.e. bio-boiler), a coherent finding. The optimum HP power coverage factor is also shifted for many of the energy supply strategies. The order of the ranking has also changed. *This indicates that the rules that are applicable for TEK10 and passive buildings does not necessarily apply for ZEB.*

With the assumption made with respect to the default values, the results are considered plausible for all the building standards. The robustness of the simulation tool has also been tested with positive outcome. It behaves in a coherent matter with the changes made in the sensitivity analysis (ref. Section 3.3).

As mentioned, the results have limited validity and should not be considered an exact representation of real life. However, the Beta-version simulation tool behaves and gets results that seem plausible. The methodology and algorithm for the Beta-version simulation tool is therefore considered sufficient for the purpose for selection of the cost-optimal energy supply strategy for non-residential ZEB during an early design phase. The simulation tool can also be used to find the best energy supply strategy for other building standards; e.g. TEK10 and passive buildings. It should in theory perform well also in a more extensive version of the simulation tool, and could be used in the development of a simulation tool for early-stage decision making with respect to energy supply strategy. However, to have a well-functioning simulation tool, the input data presented in Appendix 1 should be validated (e.g. quality insurance) and constantly updated. Also more information and input data should be collected for additional technologies included in the final version of the simulation tool.

To have a better, full scale version, of the simulation tool some issues should be addressed. Some of these are presented in Chapter 5, “Future work”.

5. FUTURE WORK

The outcome of this Master thesis is a proof of concept for a simulation tool. It is aimed for early-stage decision making with regards to the energy supply strategy. It is demonstrated by results from a Beta-version simulation tool. As stated in Chapter 4, “Conclusion”, the concept behind the tool is working, at least with the delimitations and simplifications made in this Beta-version. However, there is still a long way to go before a final simulation tool can be realised.

In Chapter 2, “The simulation tool”, the concept behind the Beta-version simulation tool algorithm is explained, with the simplifications and delimitations made. Suggestions for how the final version simulation tool should/could resolve the simplifications are mentioned throughout Chapter 2. In Table 42 these suggestions are summarized and listed.

Table 42 – Table where all suggestions for improvements to the final simulation tool are summarized.

Field of improvement	**Summary**	**Solution**
“The boundaries” (ref. Subchapter 2.2)	Some subsystems (ref. Figure 2) in the energy supply strategy are considered to be the same for all system combinations.	An examination, to see if these components will vary for different energy supply strategies and by how much, should be executed.
More system solutions (ref. Section 2.3.1)	In the Beta-version, a limited selection of energy supply technologies is introduced.	Find characteristics and input data for more relevant energy supply systems, and implement them in the simulation tool.
Dominating cooling requirement (ref. Section 2.3.2)	There is made an assumption that the heat pump always shall be able to cover the design cooling requirement, and that there is, for any given HP, a 1/1 relationship between cooling and heating power.	Implement an economic analysis procedure to see if it can be better to find other measures to reduce the cooling power requirement. And also an examination to find the correct cooling/heating power ratio should be performed.

The default values (ref. Section 2.3.2)	All the default values used in the simulations are not very accurate, as a trade-off between accuracy and resources to acquire them had to be made.	All required default values should be quality assured, and more accurate values should be found.
Backup power system (ref. Section 2.3.3)	In the Beta-version, the peak power is also said to cover the entire heating requirement.	In some cases it might be beneficial to have a cheaper system to cover the entire load, and have the peak power to just cover the peaks. A calculation procedure to find if this could be more economical should be introduced.
First room heating time step values (ref. Section 2.3.4)	The first time steps for the room heating in the SIMIEN-file, in the "Annual simulations", are unrealistically high. They are cancelled in the Beta-version.	To have a better understanding of what to do with this problem, the SIMIEN-file output should be investigated.
Return temperature from ventilation system (ref. Section 2.3.6)	The return temperature from the ventilation system is given by a fixed difference between incoming supply air and outgoing water temperature.	Use the NTU-method to find the temperature (ref. Figure 5).
Temperature fluctuations in the ground (ref. Section 2.3.7)	In the Beta-version, a temperature hybrid between ground water and energy well is applied.	Should implement both, and generally more, heat source/ sinks in the final version of the simulation tool.
Outdoor temperature limit for HP (ref. Section 2.3.7)	It is normal to have a lower outdoor temperature limit at wich a HP is swiched off. It is also normal to have an upper temperature limit for outgoing water. This does not exist for the Beta-version simulation tool.	This should be implemented in the final version of the simulation tool (e.g. -10 ºC as lower limit and 50 ºC as limit for outgoing water).
Free cooling and HP cooling mode (ref. Section 2.3.7)	In the Beta-version, a somewhat simplified free cooling solution is applied. The sink temperature is not affected by the cooling load, and the cooling COP is a fixed value.	A more precise approach, where the cooling load is accounted for and how it affects the sink temperature should be implemented. Also the actual temperature conditions should determine the HP performance.

Dew point for cooling systems (ref. Section 2.3.7)	As the temperature of a cooling surface might be below the dew point, water can condense on the surface.	A procedure that finds the actual or a good estimate of the dew point temperature for a certain operational condition should be introduced.
Peak power efficiency (ref. Section 2.3.8)	In the Beta-version, the peak power efficiencies are considered static no matter the heating load.	A calculation procedure, taking the heat load into consideration should be implemented, to find a better estimate of the efficiency.
Auxiliary energy (ref. Section 2.3.9)	In the Beta-version, auxiliary energy to operate some of the more important pumps is included. However, not all energy for pumps, fans and support systems that are depended on the energy supply strategy is implemented (e.g. fan at evaporator for ASHP). The energy used is neither transferred to the water of air it is transporting.	In the final tool all subsystems and the energy needed to operate them should be identified, and accounted for. Also the heat the subsystem emits should be accounted for.
CO_2 counterbalancing (ref. Section 2.3.10)	In the Beta-version, only the CO_2-emissions to counterbalance the operational energy is implemented. PV is the only technology that is implemented for this function.	In the final version, an option to also include emissions associated to appliances and materials should be included. Also other technologies should be implemented.
Domestic hot water (ref. Section 2.3.12)	In the Beta-version, the DHW production is done in an external optimisation loop. It is linked to the particular energy supply strategy applied.	In the final version, the DHW optimisation procedure could be independent of the system solution for the rest of the heating system. Also more technologies could be implemented, such as CO_2 HP.
GSHP disadvantage? (ref. Chapter 4)	It is found that the GSHP systems perform worse than expected.	An analysis of how the COP ratio between ASHP and GSHP is considered here, and how it should be considered in a final version should be performed. Also the actual maintenance cost of the boreholes should be investigated.

If the scope of the simulation tool is increased to that of the project report (to include all relevant technologies and energy supply strategies available on the market) there will be some additional problems that need to be resolved:

Buffer tank: If the heating or cooling system is linked to a buffer tank, and not directly to the heating or cooling emission system, another approach should be introduced with regards to heat pump operation. Instead of momentarily operation (operates when there is a requirement), the heating system could be linked to a buffer tank which calls for heating/cooling when water temperature hits a certain level. This way the HP can take a larger part of the energy requirement (by loading the tank when heating/cooling is not required in the building). This can even out power peaks and it may also shift the optimum HP power coverage factor. A methodology for such operation should be implemented, and made part of the simulation tool data base.

Energy prices: In the Beta version the energy prices are considered fixed at all times. There is no variation over the day, the week or the year. This is not necessarily the case in real life, and a procedure where shifting energy prices are included should be developed and implemented (could be favourable e.g. in the cases with buffer tanks).

Desuperheating and subcooling: The implementations of desuperheating and subcooling should be included in the cost optimization. The heating capacity of the additional heat exchangers could be used to preheat DHW, or for other useful purposes and thus increased the COP of the HP. A methodology for the implementation of such systems should be developed.

HP start/stop: As a HP has a lower power limit for operation, it might have an unwanted frequency of start/stop. As the resolution from the SIMEN file is one hour this might be difficult to find, but a methodology warning the user that a certain HP system may cause too many start/stop could be developed (not a problem with buffer tank).

Compressor efficiency: As the HP performance is given according to EN 14511, the actual compressor efficiency is not given. However, a procedure determining the efficiency based on load could be introduced to have more accurate HP performance on an annual basis.

Currency converter: As the simulation tool could be used anywhere in the world, the currency of the cost data could be converted.

There are probably a bunch of other challenges that are not mentioned here or even thought of, and which only can be found by the continuation of the work towards a final simulation tool. It is worth mentioning that the Beta-version simulation tool uses quite long time to perform a calculation where output data can be obtained (about 10 minutes on a laptop) [12]. The calculation time should therefor also be considered when the programming of the final simulation tool starts, which could mean optimizing the algorithm.

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[12] The main reason it takes so long is the iteration process explained in Figure 6. It is performed once per hour of the year form 1-100 % HP power coverage factor for six different HP configurations. $8760*100*6 = 5{,}26*10^6$ Additionally, there are some other calculations that is performed as many times, and they also add to the problem.

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Appendix 1 – Input data (default values)

In the following appendix the default values used in the simulations are listed. The values under “General” are the passive/ZEB office without night setback, and the climatic values are for Oslo. The values marked “INPUT” should be found individually for all buildings simulated. Values marked “INPUT/DEFAUL” is either climate dependent or they have a large degree of variation (e.g. from suppliers) and can changed by the user. Values marked “DEFAULT” are more indisputable, and if the user want to change them he must be certain of what he does. The list is followed by explanations to how the values are obrained.

Input data

General	Magnitude	Unit	
Power room heating	44.6	kW	(INPUT)
Power ventilation heating	18.3	kW	(INPUT)
Energy use DHW	12000	kWh	(INPUT)
Building size	2394.2	m2	(INPUT)
Power room cooling	0	kW	(INPUT)
Power ventilation cooling	14.4	kW	(INPUT)
Energy recovery unit	0.85	-	(INPUT/DEFAULT)
Design conditions			
Indoor temperature at DOT winter	20	ºC	(INPUT/DEFAULT)
Design outdoor temperature (DOT) winter	-20	ºC	(INPUT/DEFAULT)
Indoor temperature at DOT summer	26	ºC	(INPUT/DEFAULT)
Design outdoor temperature (DOT) summer	26.7	ºC	(INPUT/DEFAULT)
Heat pump data			
Nominal condensation temperature	35	ºC	(DEFAULT)
Nominal evaporation temperature	7	ºC	(DEFAULT)
Nominal COP	4.15	-	(INPUT/DEFAULT)
Isentropic efficiency compressor	0.7	-	(INPUT/DEFAULT)
Performance reduction			
Power reduction per degree cond. up	0.005	-	(DEFAULT)
Power reduction per degree evap. down	0.035	-	(DEFAULT)
COP reduction per degree cond. up	0.025	-	(DEFAULT)
COP reduction per degree evap. down	0.025	-	(DEFAULT)
Heat exchanger temperature drop			
Temperature drop in "general" heat exchangers (ingoing/outgoing)	3	K	(INPUT/DEFAULT)

Ground source/sink temperaturesand characteristics			
Annual mean ground temperature	8	ºC	(INPUT/DEFAULT)
Temperature amplitude	2	K	(INPUT/DEFAULT)
Time of the year with highest temperature (early September)	5833	hour	(DEFAULT)
Energy extraction per meter borehole	7.5	W/mK	(INPUT/DEFAULT)
Temperature difference between water and well	4	K	(INPUT/DEFAULT)
Temperatures for domestic hot water			
Temperature for DHW	70	ºC	(INPUT/DEFAULT)
City water temperature	7	ºC	(INPUT/DEFAULT)
Cost data			
Capital cost			
Interest rate	0.07	-	(INPUT/DEFAULT)
Heat pump			
Cost per kW installed heat pump capacity	6000	NOK/kW	(INPUT/DEFAULT)
Life time HP	18	years	(INPUT/DEFAULT)
Heat source/sink			
Cost per meter borehole	280	NOK/m	(INPUT/DEFAULT)
Life time energy well	50	years	(INPUT/DEFAULT)
Electric heater (boiler)			
Cost per kW installed electric heater	500	NOK/kW	(INPUT/DEFAULT)
Life time electric heater	15	years	(INPUT/DEFAULT)
Efficiency electric heater	0.9	-	(INPUT/DEFAULT)
Bio heater			
Cost per kW installed bio heater	8000	NOK/kW	(INPUT/DEFAULT)
Life time bio heater	20	years	(INPUT/DEFAULT)
Efficiency bio heater	0.73	-	(INPUT/DEFAULT)
Natural gas heater			
Cost per kW installed gas heater	1000	d	(INPUT/DEFAULT)
Life time gas heater	15	years	(INPUT/DEFAULT)
Efficiency natural gas heater	0.8	-	(INPUT/DEFAULT)
Photovoltaic panels			
Cost per kWp installed photovoltaic	25000	NOK/kWp	(INPUT/DEFAULT)
Annual energy production per installed kWp PV	781	kWh/kWp	(INPUT/DEFAULT)
Life time photovoltaic	20	years	(INPUT/DEFAULT)
How much PV panels (m2) is needed per kWp	7.4	m2/kWp	(INPUT/DEFAULT)
Hydronic heating system with radiators (hot)			
Cost radiators (hot)	250	NOK/m2	(INPUT/DEFAULT)
Life time radiators (hot)	30	years	(INPUT/DEFAULT)
Hydronic heating system with radiators (low)			
Cost radiators (low)	300	NOK/m2	(INPUT/DEFAULT)
Life time radiators (low)	30	years	(INPUT/DEFAULT)
Hydronic cooling system with cooling beams			
Cost cooling beams	250	NOK/m2	(INPUT/DEFAULT)

Life time beams	30	years	(INPUT/DEFAULT)
Hydronic floor heating/cooling system			
Cost floor heating	400	NOK/m2	(INPUT/DEFAULT)
Life time floor heating/cooling	40	years	(INPUT/DEFAULT)
Ventilation heating battery (hot)			
Cost heating battery (hot)	1100	NOK/kW	(INPUT/DEFAULT)
Life time heating battery (hot)	30	years	(INPUT/DEFAULT)
Ventilation heating battery (low)			
Cost heating battery (low)	1300	NOK/kW	(INPUT/DEFAULT)
Life time heating battery (low)	30	years	(INPUT/DEFAULT)
Ventilation heating battery (floor)			
Cost heating battery (floor)	1500	NOK/kW	(INPUT/DEFAULT)
Life time heating battery (floor)	30	years	(INPUT/DEFAULT)
Ventilation cooling battery (cooling beams)			
Cost heating battery (low)	1500	NOK/kW	(INPUT/DEFAULT)
Life time heating battery (low)	30	years	(INPUT/DEFAULT)
Ventilation cooling battery (floor)			
Cost heating battery (floor)	1800	NOK/kW	(INPUT/DEFAULT)
Life time heating battery (floor)	30	years	(INPUT/DEFAULT)
Operational cost			
Electricity			
Electricity cost	0.8	NOK/kWh	(INPUT/DEFAULT)
Bio fuel			
Bio fuel cost	0.65	NOK/kWh	(INPUT/DEFAULT)
Natural gas			
Natural gas cost	0.95	NOK/kWh	(INPUT/DEFAULT)
Maintenance and running cost			
Heat pump			
Maintenance cost HP	0.02	NOK/inv	(INPUT/DEFAULT)
Electric heater (boiler)			
Maintenance cost electric boiler	0.005	NOK/inv	(INPUT/DEFAULT)
Bio or gas boiler			
Maintenance cost bio boiler	0.02	NOK/inv	(INPUT/DEFAULT)
Photovoltaic panels			
Maintenance cost photovoltaic panels	55	NOK/kWp	(INPUT/DEFAULT)
Pump work			
Energy use pump	0.5	kW/(l/s)	(INPUT/DEFAULT)
Emissions			
Electricity			
Emission from electricity	395	g/kWh	(INPUT/DEFAULT)

Bio fuel			
Emissions from bio fuel	14	g/kWh	(INPUT/DEFAULT)
Natural gas			
Emissions from natural gas	211	g/kWh	(INPUT/DEFAULT)
Photovoltaic panels			
Emissions from photovoltaic	-395	g/kWh	(INPUT/DEFAULT)
Heating system			
Highest outdoor temperature with heating requirement	17	ºC	(INPUT/DEFAULT)
Design temperatures for radiators (hot)			
Supply temperature at highest outdoor temperature	29	ºC	(INPUT/DEFAULT)
Supply temperature at DOT	60	ºC	(INPUT/DEFAULT)
Return temperature at DOT	50	ºC	(INPUT/DEFAULT)
Design temperatures for radiators (low)			
Supply temperature at highest outdoor temperature	27	ºC	(INPUT/DEFAULT)
Supply temperature at DOT	50	ºC	(INPUT/DEFAULT)
Return temperature at DOT	40	ºC	(INPUT/DEFAULT)
Design temperatures for floor heating			
Supply temperature at highest outdoor temperature	25	ºC	(INPUT/DEFAULT)
Supply temperature at DOT	35	ºC	(INPUT/DEFAULT)
Return temperature at DOT	30	ºC	(INPUT/DEFAULT)
Radiator exponent			
Radiator exponent	1.3	-	(DEFAULT)
Floor heating exponent			
Floor heating exponent	1.1	-	(DEFAULT)
Heating battery			
Heating battery heat exchanger efficiency	0.5	-	(DEFAULT)
Temperature difference between water out and air in	10	K	(INPUT/DEFAULT)
Cooling system			
COP-factors for the cooling system			
COP (SPF) cooling mode ground	5.5	-	(INPUT/DEFAULT)
COP (SPF) cooling mode air	3.5	-	(INPUT/DEFAULT)
Outdoor temperature where maximum supply temperature occurs			
Lowest outdoor temperature with cooling requirement	17	ºC	(INPUT/DEFAULT)
Design temperatures for cooling beams			
Supply temperature at lowest outdoor temperature	15	ºC	(INPUT/DEFAULT)
Supply temperature at DOT	10	ºC	(INPUT/DEFAULT)
Return temperature at DOT	15	ºC	(INPUT/DEFAULT)
Design temperatures for floor cooling			
Supply temperature at lowest outdoor temperature	19	ºC	(INPUT/DEFAULT)
Supply temperature at DOT	16	ºC	(INPUT/DEFAULT)
Return temperature at DOT	19	ºC	(INPUT/DEFAULT)

Cooling beam exponent			
Cooling beam exponent	1.3	-	(DEFAULT)
Floor cooling exponent			
Floor cooling exponent	1.1	-	(DEFAULT)
Cooling battery			
Cooling battery heat exchanger efficiency	0.5	-	(DEFAULT)
Temperature difference between water in and air out (cooling beam)	6	K	(INPUT/DEFAULT)
Temperature difference between water in and air out (floor)	4	K	(INPUT/DEFAULT)

In the following table, the input data is explained and were the values are found is described. All values marked “no source” has an additional tag: “(high), (medium) or (low)”, describing the authors uncertainty ranking, where high being most uncertain.

General	Description
Power room heating	Design condition (building specific)
Power ventilation heating	Design condition (building specific)
Energy use DHW	Design condition (building specific)
Building size	Design condition (building specific)
Power room cooling	Design condition (building specific)
Power ventilation cooling	Design condition (building specific)
Energy recovery unit	Design condition (building specific)
Design conditions	
Indoor temperature at DOT winter	Normal indoor temperature in winter
Design outdoor temperature (DOT) winter	DOT Oslo climate
Indoor temperature at DOT summer	Max. recommended summer indoor temp.
Design outdoor temperature (DOT) summer	DOT Oslo climate
Heat pump data	
Nominal condensation temperature	Standard for test conditions EN 14511
Nominal evaporation temperature	Standard for test conditions EN 14511
Nominal COP	Average of a range of HPs from report (Løtveit, 2012)
Isentropic efficiency compressor	Typical compressor efficiency (Stene, 2013)
Performance reduction	
Power reduction per degree cond. up	From the course TEP 4260 (NTNU)
Power reduction per degree evap. down	From the course TEP 4260 (NTNU)
COP reduction per degree cond. up	From the course TEP 4260 (NTNU)
COP reduction per degree evap. down	From the course TEP 4260 (NTNU)
Heat exchanger temperature drop	
Temperature drop in "general" heat exchangers (hx) (ingoing/outgoing)	No source (low)
Ground source/sink temperaturesand characteristics	
Annual mean ground temperature	From supervisor Laurent Georges

Temperature amplitude	Hybrid between energy well and groundwater
Time of the year with highest temperature (early September)	From supervisor Laurent Georges
Energy extraction per meter borehole	From supervisor Jørn Stene
Temperature difference between water and well	No source (low)
Temperatures for domestic hot water	
Temperature for DHW	No source (low)
City water temperature	No source (low)
Cost data	
Capital cost	
Interest rate	No source (low)
Heat pump	
Cost per kW installed heat pump capacity	Average value from report (Løtveit, 2012)
Life time HP	From supervisor Jørn Stene
Heat source/sink	
Cost per meter borehole	Average value from report (Løtveit, 2012)
Life time energy well	No source (low)
Electric heater (boiler)	
Cost per kW installed electric heater	No source (high)
Life time electric heater	No source (medium)
Efficiency electric heater	From SIMIEN (ProgramByggerne)
Bio heater	
Cost per kW installed bio heater	No source (high)
Life time bio heater	No source (medium)
Efficiency bio heater	From SIMIEN (ProgramByggerne)
Natural gas heater	
Cost per kW installed gas heater	No source (high)
Life time gas heater	No source (medium)
Efficiency natural gas heater	From SIMIEN (ProgramByggerne)
Photovoltaic panels	
Cost per kWp installed photovoltaic	Value from report (Løtveit, 2012)
Annual energy production per installed kWp PV	From supervisor Laurent Georges
Life time photovoltaic	No source (medium)
How much PV panels (m2) is needed per kWp	Intern calculation
Hydronic heating system with radiators (hot)	
Cost radiators (hot)	From report (COWI, 2012)
Life time radiators (hot)	No source (medium)
Hydronic heating system with radiators (low)	
Cost radiators (low)	No source (high)
Life time radiators (low)	No source (medium)

Hydronic cooling system with cooling beams	
Cost cooling beams	No source (high)
Life time beams	No source (medium)
Hydronic floor heating/cooling system	
Cost floor heating	No source (high)
Life time floor heating/cooling	No source (medium)
Ventilation heating battery (hot)	
Cost heating battery (hot)	No source (high)
Life time heating battery (hot)	No source (high)
Ventilation heating battery (low)	
Cost heating battery (low)	No source (high)
Life time heating battery (low)	No source (high)
Ventilation heating battery (floor)	
Cost heating battery (floor)	No source (high)
Life time heating battery (floor)	No source (high)
Ventilation cooling battery (cooling beams)	
Cost heating battery (low)	No source (high)
Life time heating battery (low)	No source (high)
Ventilation cooling battery (floor)	
Cost heating battery (floor)	No source (high)
Life time heating battery (floor)	No source (high)
Operational cost	
Electricity	
Electricity cost	From SIMIEN (ProgramByggerne)
Bio fuel	
Bio fuel cost	From SIMIEN (ProgramByggerne)
Natural gas	
Natural gas cost	From SIMIEN (ProgramByggerne)
Maintenance and running cost	
Heat pump	
Maintenance cost HP	No source (low)
Electric heater (boiler)	
Maintenance cost electric boiler	No source (medium)
Bio or gas boiler	
Maintenance cost bio boiler	No source (medium)
Photovoltaic panels	
Maintenance cost photovoltaic panels	From report (Løtveit, 2012)
Pump work	
Energy use pump	From SIMIEN (ProgramByggerne)

Emissions	
Electricity	
Emission from electricity	From SIMIEN (ProgramByggerne)
Bio fuel	
Emissions from bio fuel	From SIMIEN (ProgramByggerne)
Natural gas	
Emissions from natural gas	From SIMIEN (ProgramByggerne)
Photovoltaic panels	
Emissions from photovoltaic	From SIMIEN (ProgramByggerne)
Heating system	
Highest outdoor temperature with heating requirement	No source (low)
Design temperatures for radiators (hot)	
Supply temperature at highest outdoor temperature	Chosen value
Supply temperature at DOT	Chosen value
Return temperature at DOT	Chosen value
Design temperatures for radiators (low)	
Supply temperature at highest outdoor temperature	Chosen value
Supply temperature at DOT	Chosen value
Return temperature at DOT	Chosen value
Design temperatures for floor heating	
Supply temperature at highest outdoor temperature	Chosen value
Supply temperature at DOT	Chosen value
Return temperature at DOT	Chosen value
Radiator exponent	
Radiator exponent	From supervisor Laurent Georges
Floor heating exponent	
Floor heating exponent	From supervisor Laurent Georges
Heating battery	
Heating battery heat exchanger efficiency	No source (found for a unit using NTU-method)
Temperature difference between water out and air in	No source (high)
Cooling system	
COP-factors for the cooling system	
COP (SPF) cooling mode ground	No source (medium)
COP (SPF) cooling mode air	No source (medium)
Outdoor temperature where maximum supply temperature occurs	
Lowest outdoor temperature with cooling requirement	No source (medium)
Design temperatures for cooling beams	

Supply temperature at lowest outdoor temperature	Chosen value
Supply temperature at DOT	Chosen value
Return temperature at DOT	Chosen value
Design temperatures for floor cooling	
Supply temperature at lowest outdoor temperature	Chosen value
Supply temperature at DOT	Chosen value
Return temperature at DOT	Chosen value
Cooling beam exponent	
Cooling beam exponent	No source (high, not used)
Floor cooling exponent	
Floor cooling exponent	No source (high, not used)
Cooling battery	
Cooling battery heat exchanger efficiency	No source (medium)
Temperature difference between water in and air out (cooling beam)	No source (high)
Temperature difference between water in and air out (floor)	No source (high)

As seen, the number of values obtained without any source is significant. The values marked "(low)" are qualifyed guesses, and are likely to be close to what would be found in a thorough analysis. The values marked "(medium)" are good guesses, and are probably either not so far away from an actual value. Whereas the values marked "(high)" are wild guesses, and it is difficult to say if they are near the target.