NTNU – Trondheim
Norwegian University of
Science and Technology

Cost Optimality of Energy Systems in Zero Emission Buildings in Early Design Phase

Pablo Barbado Baranda

Master's Thesis
Submission date: July 2014
Supervisor: Vojislav Novakovic, EPT
Co-supervisor: Igor Sartori, EPT

Norwegian University of Science and Technology
Department of Energy and Process Engineering

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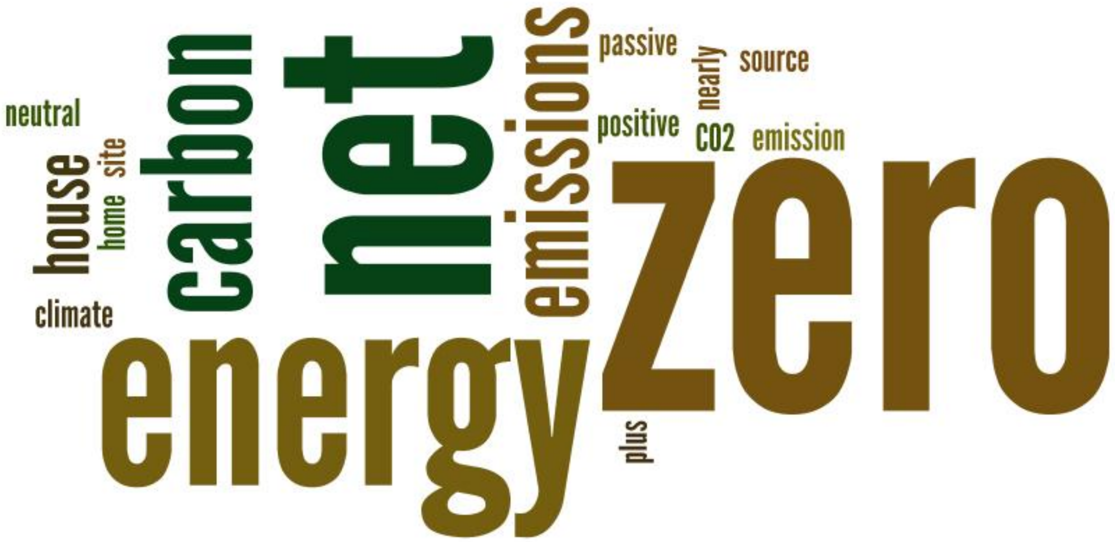

NTNU

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Trondheim, July 2014

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of Science and Technology
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Department of Energy and Process Engineering

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Abstract

During the uncontrolled consumption period the building sector has come to account one of the greatest proportions of greenhouse gas emissions and energy use in industrial countries. In this context, European countries have decided to address the environmental challenge by promoting the use of renewable energies and the implementation of low energy consumption requirements. For these reasons, zero emission buildings, which have a net zero annual energy demand, were regarded as a possible solution. And everything points to believe that they will continue to be crucial in a recent future.

Consultants and contractors have shown the need towards a better understanding and knowledge regarding the selection of renewable energy supply solution for ZEBs. Accordingly, this Mater Thesis aims to explain how to use the new methodology for a cost-optimal selection of energy systems in early design phase analysis. It consists on a number of guidelines and Excel files that serve as templates for different calculations. The project is part of the development of a decision support method that automates the process of selecting the best system, in this particular case in office buildings.

This early design phase study is not only focused on giving a cost-optimal alternative but also on performing a full analysis in terms of energy performance. It also shows the steps for both the energy systems dimension and the selection of office building parameters. A concept office building with four storeys is selected and modelled in connection with the Norwegian ZEB centre's project report 8. Following the Norwegian NZEB definition, the simulation software IDA-ICE is used as a tool for modelling the building and simulating the energy demand. It analyses six different energy supply combinations which were selected between available renewable technologies in Norway. In comparison to the previous study applied in residential buildings, this project introduces the building's cooling demand as a new feature of the analysis. Therefore, reversible heat pumps, free-cooling with the ground and chillers are also taken into account. Further, energy systems are economically compared by using global cost calculations, following the European Cost Optimal Methodology.

Results are given in a graph where global costs and CO_2 emissions produced by the energy balance of the building are shown in each axis. Finally the cost-optimal energy supply, the system with lower global costs, is selected like the most suitable option. In addition, the building energy performance is also discussed as an important parameter to be considered in the decision making process. At the end, the sensitivity analysis shows stable results with regard to changes in energy price development and PV area.

Resumen

Tras un periodo de consumo descontrolado, el sector de la construcción ha acabado representando una de las mayores fracciones de emisiones totales de efecto invernadero y consumo energético en los países industrializados. En este contexto, los países Europeos han decidido abordar este desafío medioambiental promoviendo el uso de energías renovables y la implementación de requisitos para un bajo consumo energético. Por esta razón los edificios de cero emisiones, los cuales tienen una demanda energética nula, se consideraron como una posible solución, y todo indica a que continuarán siéndolo en un futuro cercano.

Empresas consultoras y contratistas han mostrado la necesidad de lograr una mejor compresión y conocimiento sobre cómo seleccionar el suministro energético en los ZEBs. En este sentido, esta Master Tesis trata de explicar cómo ha de utilizarse la nueva metodología para la selección del sistema energético más rentable en un análisis en primera fase de diseño. Esta, consiste en una serie de directrices y archivos Excel que sirven como plantillas en diferentes cálculos. El proyecto es parte del desarrollo de un método de apoyo a la toma de decisiones que automatiza el proceso de selección del mejor sistema energético, en este caso en concreto en edificios de oficinas.

El estudio en fase inicial de diseño no sólo se centra en dar la alternativa más rentable, sino que también en desarrollar un análisis completo en términos de eficiencia energética, mostrando además los pasos para dimensionar los sistemas energéticos y definir los parámetros del edificio de oficinas. Se selecciona y modela un edificio conceptual de oficinas de cuatro plantas en conexión con el informe número 8 del centro noruego ZEB. Siguiendo la definición NZEB noruega, se usa el programa de simulación IDA-ICE como herramienta para modelar el edificio y simular la demanda energética. Con él, se analizan seis combinaciones diferentes de suministros energéticos que han sido seleccionados entre las tecnologías renovables disponibles en Noruega. En comparación con el estudio previo aplicado a edificios residenciales, este proyecto introduce como nueva característica del análisis la demanda de refrigeración del edifico. Por lo tanto también se tienen en cuenta: bombas de calor reversibles, refrigeración gratuita con el suelo y máquinas frigoríficas. Los sistemas se comparan entre ellos mediante el cálculo de los costes globales siguiendo la "European Cost Optimal Methodology".

Los resultados se resumen en gráficas que muestra las emisiones de CO_2 producidas tras el balance energético y los costes globales en cada uno de los ejes. Finalmente el suministro energético más rentable, el que ostenta los costes globales más bajos, se elige como el más adecuado. Se discute además sobre la eficiencia energética al ser este un parámetro importante en la toma de decisión. Al final el análisis de sensibilidad demuestra que los resultados son estables respecto a cambios en el desarrollo del precio energético y del área de paneles fotovoltaicos.

Sammendrag

I løpet av den ukontrollerte forbrukerperioden har byggesektoren endt opp med å bli årsaken til en av de største andelene av klimagassutslipp og energibruk i industriland. I denne sammenhengen har europeiske land besluttet å løse miljøutfordringen ved å fremme bruken av fornybar energi og ved hjelp av implementering av krav til lavt energiforbruk. Derfor betraktes nullutslippsbygg, med null netto årlig energibehov, som en mulig løsning. Så alt peker mot at de vil være avgjørende i tiden fremover.

Konsulenter og entreprenører har uttrykt behov for en bedre forståelse og mer kunnskap knyttet til valg av fornybar energiforsyning løsning for ZEBs. Formålet med denne masteroppgaven er å forklare hvordan en bruker den nye metodikken for et kostnadsoptimalt valg av energisystemer i tidlige designerfase-analyser. Den består av en rekke av retningslinjer og Excel-filer som fungerer som maler for ulike beregninger. Prosjektet er en del av utviklingen av en beslutningsstøttemetode som automatiserer prosessen med å velge det beste systemet, hvor det i dette tilfellet gjelder kontorbygg.

Denne studien av tidlig designfase har ikke bare fokus på å gi et kostnadsoptimalt alternativ, men også på utførelsen av en fullstendig analyse av energiytelse. Den viser også fremgangsmåten for både energisystemers dimensjon og valg av parametere for kontorbygg. Et konsept for kontorbygg med fire etasjer er valgt og modellert i henhold til den norske ZEBsenterets prosjektrapport 8. Simuleringsprogrammet IDA-ICE brukes etter norsk NZEB definisjon som et verktøy for å modellere bygningen og simulere energibehovet. Det analyserer seks forskjellige energiforsyningskombinasjoner som ble valgt mellom tilgjengelige fornybare teknologier i Norge. Sammenlignet med tidligere undersøkelser gjort på boliger, introduserer dette prosjektet byggets kjølebehov som en ny funksjon i analysen. Derfor er det også tatt hensyn til reversible varmepumper, frikjøling med bakken og kjøleenheter. Videre er energisystem sammenlignet med hverandre ved å bruke globale kostnadskalkyler som bruker ”the European Cost Optimal Methodology”.

Resultatene vises i en graf hvor globale totalkostnader og CO2-utslipp som produseres ut fra bygningens energibalanse er vist på hver sin akse. Og mot slutten er kostnadsoptimal energitilførsel, systemet med laveste totale kostnader, valgt som det mest hensiktsmessige alternativet. I tillegg diskuteres bygningens energiytelse som er en viktig parameter som må tas hensyn til i beslutningsprosessen. Til slutt viser sensitivitetsanalysen stabile resultater med hensyn på endringer i energiprisutvikling og område av fotoelektriske paneler.

NTNU
Norwegian University
of Science and Technology

Department of Energy
and Process Engineering

EPT-M-2014-09

MASTER THESIS

for

Student Pablo Barbado Baranda

Spring 2014

Cost optimality of energy systems in ZEB in early design phase

Kostnadsoptimalisering av energisystemer for ZEB tidlig i prosjekteringen

Background and objective

A survey among relevant consultants and contractors has showed the need for better knowledge and more systematic information in order to make decisions regarding the selection of system for energy supply of ZEBs (Zero Emission Buildings). The ZEB centre aims to develop a methodology for early design phase analysis of energy supply systems in ZEBs that will include both a calculation tool and an information database. This assignment will be part of this development.

The main objective of this work is to evaluate the cost optimality of different energy systems for a ZEB office using the European cost optimal methodology introduced in the context of the EPBD (Energy Performance of Buildings). Both modelling and evaluation of energy performance of the building and its energy systems and calculation of costs are part of this assignment.

Modelling of a typical new office building will be performed using the dynamic simulation tool IDA-ICE, building upon and further improving and detailing the model developed during the project assignment in autumn. Calculation of costs will be based on the cost database available at EPT and previously collected in other project assignments. If necessary, such database should be updated by the student.

This assignment is closely related to The Research Centre on Zero Emission Building at NTNU and SINTEF (FME ZEB) that has the vision to eliminate the greenhouse gas emissions caused by buildings. The main objective of FME ZEB is to develop competitive products and solutions for existing and new buildings that will lead to market penetration of buildings that have zero emissions of greenhouse gases related to their production, operation and demolition.

The following tasks are to be considered:

1. Describe the European cost optimal methodology, incl. both financial and macroeconomic analysis, and define suitable energy prices and CO2 prices to be applied. Economic analysis of the electricity exchanged with the grid will also be included in the operating costs (ref-Plusskunder ordningen).
2. Choose a number of energy system combinations, e.g. heat pump plus photovoltaic, and describe their main technical and economic characteristics. The energy systems will include combinations of: Heat Pumps (HP), Biomass Boiler (BB), District Heating (DH), Photovoltaic (PV) and Solar Thermal (ST).
3. Model a new ZEB office with the different energy systems and simulate the energy performance at hourly level, using IDA-ICE.
4. Collaborate, at least in the form of providing results from simulations, in writing the Guidelines for early design phase analysis of energy system in ZEB offices.
5. Use the energy flows from simulation and cost from previously developed database in order to calculate cost optimality for the various systems using both primary energy and carbon emission factors as metrics for the energy flows.
6. Perform a sensitivity analysis for uncertainties in investment costs as well as energy prices. Discuss the results.

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

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

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

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, 14. January 2014

Olav Bolland
Department Head

Vojislav Novakovic
Academic Supervisor

Research Advisor: Igor Sartori, Postdoc

Preface

This Master Thesis marks the completion of my studies as a industrial engineer and my Erasmus year in Trondheim. Undoubtedly now I am able to confirm that Erasmus is a lifetime experience as well as a way to discover the real meaning of living abroad in a totally different culture. This is the end of a life stage and the beginning of a new period that opens up new possibilities.

Countless number of pages full of information makes the difference between my arrival to Trondheim, without having a clear idea of what energy systems, zero emission buildings and energy efficiency meant, and my departure; now with a real understanding of the subject. In the following pages, I have tried to explain the process in every possible detail in order to ensure that future students and people interested in the topic can easily interpret the meaning. As my first piece of knowledge posted on internet, I only hope that these pages could serve as a learning tool for everyone that wants to learn something new. Like other publications and projects have helped me along this year. No doubt, reading new information is equally as important for writing as the ability of developing the individual thinking. "Thinking outside the box" is the way of encouraging our creativity, one of the most important aspects for a researcher.

Firstly, I would like to express my gratitude to Vojislav Novakovic and Igor Sartori for letting me participate in this project and allowing me to discover a topic which I am comfortable working with. Likewise, I would like to use this opportunity to sincerely give thanks to everyone that has been involved in this project writing process. Specially, thanks to Laura Ferrer for helping me with the understanding of the Excel files and Ángel Galíndez for the English corrections and advice. Thanks to my Norwegian family and all the people that I have met for this unforgettable year.

Pablo Barbado Baranda

Trondheim, July 12, 2014

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Abbreviations

Symbol	Description
PEF	Primary Energy Factor
E	Energy
ZEB	Zero Emission Building
NZEB	Net Zero Emission Building
ST	Solar Thermal Collectors
PV	Photovoltaic panels
HP	Heat Pump
GSHP	Ground Source Heat Pump
ASHP	Air Source Heat Pump
CHP	Combined Heat and Power
BB	Biomass Boiler
EB	Electric Boiler
El	Electricity
GHG	Greenhouse gas emissions
COP	Coefficient of performance
DHW	Domestic hot water
U-Value	Thermal Transmittance
NOK	Norwegian currency

1. Introduction

1.1 Background

In 1997, European Member States agreed to sign the Kyoto Protocol with the commitment of reducing their collective emissions and limit global warming. After the international agreement, the European Union has strongly promoted a continuous development of national plans and new targets to cut greenhouse gas emissions. For 2050, the target set is an 80% reduction in GHG emissions compared to the 1990 levels. Countries like Norway have started to set new measures and requirements in their national plans to reduce energy consumption and increase share of energy from renewable sources.

For 2020, European Union is committed to the goal of a first 20% reduction. Towards this objective, Member States set the 20-20-20 targets to transform Europe into a highly-efficient and low carbon economy. These targets represent the approach to climate and energy policy that countries should follow to combat the climate change. Three key objectives were set for 2020 [1]:

- A 20% reduction in EU greenhouse gas emissions from 1990 levels.
- Raising the share of EU energy consumption produced from renewable resources to 20%.
- A 20% improvement in the EU's energy efficiency.

Buildings account for around a 40% of total energy consumption and 36% of CO_2 emissions in Europe [2]. Save energy in buildings is therefore one of the European Union’s most important points in the strategy of achieving a real transition to a sustainable energy system and a resource efficient economy by 2020. To address this problem, energy management and efficiency in buildings has become an important field of study for the development of new measures to reduce energy dependency and greenhouse emissions. The 2010 recast of the Energy Performance in Buildings (EPBD) [3], a European directive that includes all these measures, set the framework and boundaries to keep working towards the same objective. The directive urges Member States to develop policies and take action in order to stimulate the transformation of the building sector with the implementation of minimum requirements for low energy buildings. It also introduced the concept of nearly zero energy building, a building with high energy performance that is set to be the standard for all new buildings by 2020. Thereby, the promotion of nearly zero energy buildings and zero emission buildings (ZEB) is seen like the best option to accomplish the environmental challenge and work towards a paradigm of decentralized energy generation. Besides, this kind of buildings address the three 20-20-20 targets at the same time.

Norway is one of the most advanced countries in trying to reach the EU target goals. A high public investment and government involvement in the research of new energy systems and their efficiency improvement is making the country a leader in the matter. In that direction, the country has created national standards to set minimum requirements for new and existing buildings, which are updated every few years. In 2009, the Norwegian government created the first eight Centres for Environment-friendly Energy Research (FME) in order to solve the specific challenges in the field of energy and environment. NTNU and Sintef are host organizations of few of these national research centres and also partners in some others. Specifically, the Norwegian University of Science and Technology (NTNU) hosts the Research Centre on Zero Emission Buildings (ZEB), which copes with issues in energy efficiency in buildings [4]. The centre is funded until 2016 with the aim of encouraging Norway as a leader in research, innovation and implementation of low energy buildings.

1.2 EPBD application and regulations in Norway

On 19 May 2010, the EU adopted the Energy Performance of Buildings Directive 2010/31/EU (EPBD) as a tool to promote the energy performance of buildings within the European Union through cost-effective measures. It set up 31 articles with recommendations regarding different aspects that influence the building energy use. Under this directive, Member States shall implement a methodology for the calculation of energy performance, establish minimum energy requirements, create an energy certificate and increase the number of nearly zero-energy buildings. Nevertheless, it does not specify a detailed calculation methodology, leaving it up to Member states to decide the details of how to apply it. For that reason, Norway has defined its own standards and measures after the interpretation of some of the directive articles [3]:

- Setting of minimum energy performance requirements

“Article 4: Member States shall take the necessary measures to ensure that minimum energy performance requirements for buildings or building units are set with a view to achieving cost-optimal levels.”

The Norwegian Government has developed important standards to set the necessary minimum requirements for buildings. Two of them have been used in this project to define the building model parameters:

- Norwegian national standard for calculation of energy performance of buildings – NS 3031 (2010) [5]
- Requirements for passive house of non-residential buildings – NS 3701 (2012) [6]

The national standard is based on the European standard EN ISO 13790 and serves for the calculation of energy performance while controlling if minimum requirements have been met. It establishes average consumptions of domestic utilities such as: hot water, lighting and equipment that different kind of buildings have. It also gives standard values for air flows, thermal bridges or set point temperatures.

NS 3701 for non-residential buildings, together with NS 3700 for residential buildings were created as an adaptation to the German passive house definition introduced by "Passivhaus Institut". This standard is a Norwegian definition for passive houses, regarded as environmentally friendly buildings with a very low energy need, and low-energy buildings. It establishes certain requirements of energy demand for heating, cooling, lighting and in addition a set of requirements for heat losses from the building envelope due to heat transmission. In the following table 1.1, the most important parameters taken from the standard to create a building model are shown:

Parameters	**NS 3701 requirements**
U-value external walls	0.10-0.12 W/m^{2}k
U-value roof	0.08-0.09 W/m^{2}k
U-value floor	0.08 W/m^{2}k
U-value windows	≤0.08 W/m^{2}k
Total thermal bridge	≤0.03 W/m^{2}k
Ventilation heat exchanger efficiency	≥ 80 %
SFP-factor (Specific Fan Power)	≤1.5 kW/(m^3/s)
Leakage at 50 Pa, n_{50}	≤0.6 h^{-1}

Table 1.1: Most important requirements in the standard NS 3701

- Nearly zero-energy buildings

"Article 9: Member States shall ensure that by 31 December 2020, all new buildings are nearly zero-energy buildings; and after 31 December 2018, new buildings occupied and owned by public authorities are nearly zero-energy buildings. Member States shall draw up national plans for increasing the number of nearly zero-energy buildings. These national plans may include targets differentiated according to the category of building."

The measure taken by Norway of creating the Research Centre of Zero Emission Buildings is an act that demonstrates the Norwegian willingness of reaching the target. Norway expects after this investment to be at the forefront of the building efficiency and energy supply systems development research.

- Calculation of cost-optimal levels of minimum energy performance requirements

"Article 5: The Commission shall establish a comparative methodology framework for calculating cost-optimal levels of minimum energy performance requirements for buildings and building elements. Cost-optimal levels shall be calculated in accordance with the comparative methodology framework once the framework is in place."

In 2012, the European commission established a methodology framework for calculating cost optimal levels of minimum energy performance requirements for buildings and building elements. This thesis, as a project proposed by the Norwegian ZEB centre, aims to show the necessary knowledge that is needed to apply the cost optimal methodology in any Norwegian office building.

- Energy performance certificates

"Article 11: Member States shall lay down the necessary measures to establish a system of certification of the energy performance of buildings. The energy performance certificate shall include the energy performance of a building and reference values."

The Norwegian Ministry of Petroleum and Energy with the Ministry of Local Government and Regional Development established after the EPBD publication a label system for non-residential buildings according to the primary energy consumption. Therefore, depending on the primary energy demand of the building, it will be rated with a letter going from A to G.

1.3 Objectives and structure

The objective of this Master Thesis is to give the necessary guidelines to perform a cost-optimal analysis of energy systems in early design phase. It is predominantly focused on zero emission office buildings with cooling demand during the summer. A methodological approach in early design phase is applied in a practical case by using the programs IDA-ICE and Excel. This methodology relies on two main concepts: the NZEB balance and the European Cost Optimal Methodology.

The project starts with a theoretical approach (Chapter 2) to the NZEB concept by explaining what exactly means the NZEB balance and how weighting factors should be used. It further introduces the key points that shape the Norwegian NZEB definition. The cost-optimal methodology is also presented in this chapter, aiming to show the equations that will be later used for global cost calculations. Then, there is an introductory definition of every available energy system that could be an alternative in a Norwegian analysis. Moreover, IDA-ICE, the simulation software used for energy performance simulations, is briefly described at the end of this section.

Since chapter 3 explains which guidelines need to be followed and how all the necessary parameters should be defined in a real analysis, it has been given the name of Approach. In the beginning, the early design phase methodology for the analysis of energy supply systems is introduced. It is basically based on a flow chart that ends with the cost-optimal comparison of different energy supply alternatives. In the middle of the process, IDA-ICE results should be collected and pasted in some Excel files that perform desired calculations. For a better understanding, the methodology is applied as an example in a conceptual office building. Thus, this chapter seeks to specify in a great detail how model parameters have to be set in IDA-ICE. Building model characteristics, energy systems and economic parameters are therefore analysed in a practical application.

Once all the input data has been finally set in the model, IDA-ICE simulations and Excel calculations are performed. Chapter 4 gives the results for a normal energy price development scenario. Overall, six different base heating systems with their corresponding cooling system and a fix area of PVs covering the roof are analysed. All of them are compared in accordance to the NZEB balance, the electricity mismatch and the global costs. A sensitivity analysis is done later in Chapter 5, so it can be seen how uncertain values are correlated with the results. Two additional energy price escalations are probed; one with high and the other with low development. In addition, 100 m^2 more of PVs are installed in the west façade to realized how it influences each system.

At last but not least, the obtained results as well as possible uncertainties are discussed in chapter 6. Chapters 7 and 8 respectively, summarize the project in six conclusions and give some ideas that can be further developed in a future study.

2. Theory

2.1 NZEB balance concept

In general terms, a ZEB is understood as a grid-connected, energy efficient building able to generate electricity by 'on-site' renewable generation systems in order to compensate its annual energy demand [7]. Hence, the concept is referred to buildings connected to an energy infrastructure that have an exchange of energy during the year, what is called a two-way energy grid. Related with this, the term Net ZEB can be used to emphasize the balance concept between building and grid. The Net ZEB approach is part of a strategy to increase the share of renewable energy within the grid infrastructure, thus reducing associated carbon emissions [8].

The NZEB balance can be represented with a simple equation of weighted values. This equation is a subtraction between the supplied energy to the grid and the building energy demand throughout the whole year. Both values should be balanced after applying the weighting factors of each energy carrier used in the building network, what will be explained in the chapter 2.2. In accordance with the equation 2.1, the Net ZEB balance will be satisfied when the weighted supply equals the weighted demand over a year.

$$\text{Net ZEB balance: } |\text{weighted supply}| - |\text{weighted demand}| = 0 \qquad \text{(Equation 2.1)}$$

A building that complies this equation is what is called a Net ZEB. When the EPBD talks about nearly Net ZEBs, it means a building with a little higher weighted demand, thereby a negative balance. Otherwise, a Net plus energy building is the one with more weighted supply energy to the grid than demand, in other words, a positive balance. All this concepts are represented in figure 2.1. In addition, the image below shows the efficiency path that a reference building, building with minimum requirements from TEK10, should follow to achieve a Net ZEB grade. A graph is plotted with weighted supply on the y-axis and weighted demand on the x-axis. To transform the performance of a normal building to a NZEB level through renovation work, energy demand (x-axis) should be reduced and generated electricity (y-axis) increased. It should be noted that the position of the reference building will change with the upcoming update of the Norwegian building code in 2015 [9]. TEK15 will modify the current minimum requirements for buildings and increase the share of renewable energy to satisfy the demand.

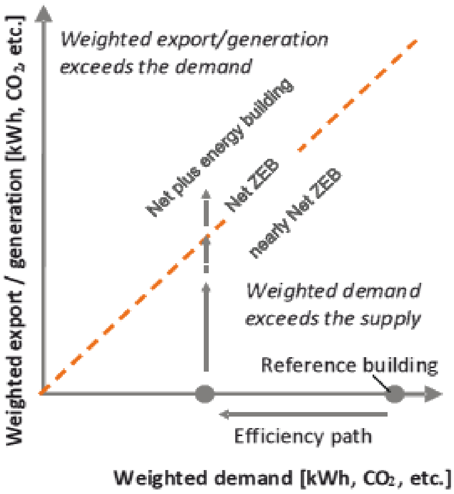


Figure 2.1: Net ZEB representation with the nearly and plus variants [7]

The balance of the equation 2.1 can be calculated in different ways. As the figure 2.2 shows, it is important to define a building system boundary to decide how the calculations will be made. Inside the boundary, the *load/generation* balance will be performed, measuring how much the building consumes and how much it can generate in a year. Otherwise, outside the boundary the delivered/exported or *import/export* balance is calculated, taking into account the energy flow crossing the boundary. Nevertheless, such calculation can be performed as long as all consumptions are known, including the self-consumption [7]. The *load/generation* balance is comparing with the others, done in more simplified manner. Since the measured energy does not cross the building system boundary, the interaction with the grid is completely neglected. This simplified calculation is equivalent to assuming that, per each energy carrier, the entire load is completely satisfied by delivered energy while generation is completely fed into the grid [8]. Therefore, it does not account the amount of self-consumed energy, i.e. the generated energy that the building is consuming in each moment of the year.

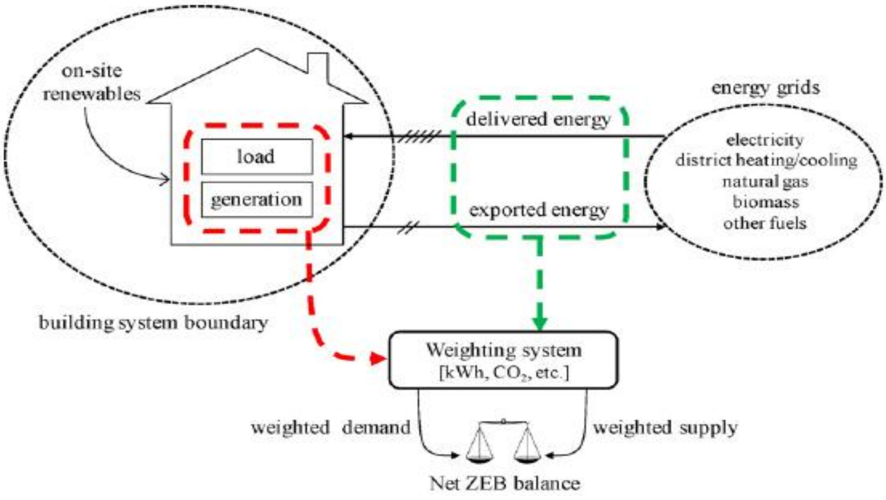


Figure 2.2: Connection between building and energy grids [8]

Alternatively, there is a third way to calculate the balance known as *monthly net balance*. Load and generation are assumed to balance every month, then monthly generation surplus or remaining load are summed up to form the annual total values. The three balances are related with each other, the main difference between them is the amount of self-consumed energy generated on-site. These three different ways to calculate the equation 2.1 can be defined analytically as:

2.1.1 Import/Export balance equations

$$\begin{cases} |\text{Export}| - |\text{Import}| = 0 & \text{(Equation 2.2)} \\ \text{Weighted imported energy} = \sum E_{imp,i} \times w_i & \text{(Equation 2.3)} \\ \text{Weighted exported energy} = \sum E_{exp,i} \times w_i & \text{(Equation 2.4)} \end{cases}$$

2.1.2 Load/Generation balance equations

$$\begin{cases} |\text{Generation}| - |\text{Load}| = 0 & \text{(Equation 2.5)} \\ \text{Weighted generation} = \sum E_{gen,i} \times w_i & \text{(Equation 2.6)} \\ \text{Weighted load} = \sum E_{load,i} \times w_i & \text{(Equation 2.7)} \end{cases}$$

2.1.3 Monthly net balance

$$\begin{cases} |\text{Monthly net generation}| - |\text{Monthly net load}| = 0 & \text{(Equation 2.8)} \\ \text{Weighted monthly net generation} = \sum E_{gen,i} \times w_i & \text{(Equation 2.9)} \\ \text{Weighted monthly net load} = \sum E_{load,i} \times w_i & \text{(Equation 2.10)} \\ E_{gen,i} = \sum \max|0, E_{gen} - E_{load}| & \text{(Equation 2.11)} \\ E_{load,i} = \sum \max|0, E_{load} - E_{gen}| & \text{(Equation 2.12)} \end{cases}$$

Where E_i stands for and energy measure, i refers to one energy carrier and w_i the weighting factor for each energy carrier. Equations have been taken from the work [8].

The figure 2.3 presents the three possible balances described above: *import/export* balance between weighted exported and delivered energy, *load/generation* balance between weighted generation and load, and *monthly net balance* between weighted monthly net values of generation and load. All the balance points are positioned in a 45 degrees dotted line that represents the Net

ZEB balance, i.e. the line where both values are equal. Furthermore, the image shows how the self-consumption makes the difference between balances. In the import/export balance in compare with the load/generation, the self-consumption reduces the amount of energy exchanged with the grid, thereby improving the building efficiency because of a lower demand. In any case, every building considered as a Net ZEB has to fulfil the balance condition.

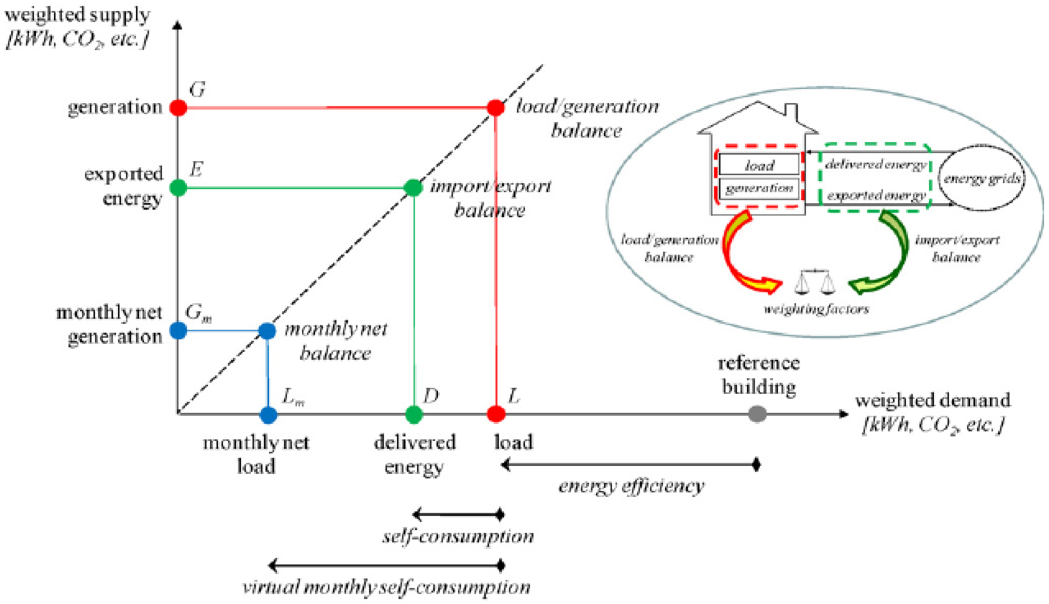


Figure 2.3: Representations of three types of balances [7]

2.2 Energy performance and weighting factors

After the introduction of the balance concept and its different equations, this part aims to go more in deep in the explanation of the energy performance calculations. The European Union has elaborated a number of standards inside the EN-EPB package that deal with the topic. Probably the most important standard related with the NZEB performance is EN 15603 [10], which presents the framework and calculation rules of energy flows and also how to use the weighting conversions. As it can be seen in figure 2.4, this standard addresses the third final step in the energy performance calculations, weighting and balancing all delivered and exported energy flows.

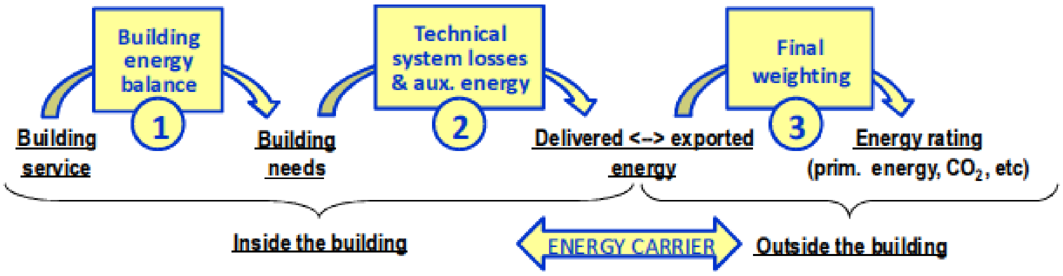


Figure 2.4: Three main steps in energy performance calculations [11]

Consequently, the term energy performance can be easily described in the equation (2.13) which is used for every metric [11]. The equation is related with the NZEB balance equation (2.1), but expressed in a different way. A building with a positive energy balance (Net Plus Energy Building) will have a negative energy performance in accordance with both equations. Even if this affirmation can seem meaningless, it is important to realize that the calculation is done per each energy carrier; thus the carrier that generates a negative energy performance will compensate other energy carrier's contribution.

$$\text{Energy performance} = \text{Weighted delivered energy} - \text{Weighted exported energy}$$
(Equation 2.13)

As it can be deduced from the previous paragraphs, setting consistent and reliable weighting factors is an important step to be able to find the real energy performance of the building. These factors are a political tool of environmental management typically decided with national statics. They are necessary when comparing energy carriers that are used in a building, such as coil, oil, electricity, district heating, etc. Each of them has different losses in its entire energy chain (extraction from energy sources, conversion processes, transmission and distribution), what means that they are sometimes expressed in distinct units and leading to a variety of impacts. Therefore, weighting factors help to find a common expression for all energy carriers in order to use them in the same calculation. The four most common metrics used for energy performance calculations are: primary energy (PE), site energy, CO_2-eq emissions and energy costs [12]. According to the EPBD the metric that should be used during the NZEB balance is primary energy. However, some countries like Norway, as it will be explained in the next chapter, prefer carbon emissions like their primary metric. As it is shown in the report [13], most of the research studies about low, passive, nearly and net zero energy buildings use primary energy and carbon emissions as a metrics.

The EPBD states: "The energy performance of a building shall be expressed in a transparent manner and shall include an energy performance indicator and a numeric indicator of primary energy use, based on primary energy factors per energy carrier, which may be based on national or regional annual weighted averages or a specific value for on-site production". This job should be done in each one of the European countries since they have different national electricity mixes, what leads to completely disparate values. The main reason for this is that weighting factors should reflect reliably the specific national or local power grid structure.

2.2.1 Primary energy factors

Primary energy is energy in its original form, which is found in nature and has not been subjected to any conversion or transformation process. It is presented both in renewable energy sources (sun, wind, geothermal and biomass) and non-renewable sources (coil, crude oil and uranium). For a human use of natural resources, the primary energy is transformed through conversion processes in more suitable energy forms, such as electricity or refined fuels. The PEF is an efficiency indicator that gives a view of the losses during these transformations. It can be defined as a relation between primary energy and delivered energy after the conversion, of which is expressed in the equations (2.14) and (2.15). The following equations have been obtained from [14]:

$$\text{Primary energy x System efficiency} = \text{Delivered energy} \qquad \text{(Equation 2.14)}$$

$$\text{Delivered energy x PEF} = \text{Primary energy} \qquad \text{(Equation 2.15)}$$

Two different values of PEFs can be used, depending on whether it is preferred a perspective of total primary energy factors or non-renewable factors. When using total primary energy factors, all the overheads of delivery to the point of use are taken into account, including the energy from renewable energy sources. Non-renewable primary energy factors are the same but excluding the renewable energy component. Hence, non-renewable factors are usually lower than total ones. Each country makes the choice between taking one or the other depending on the energy carrier that they want to favour. The election normally responds to political reasons, leading to lower conversion factors for those energy supply solutions that want to be stimulated. Furthermore, political adjusted factors are used for the same purpose; to promote or discourage the adoption of certain technologies and energy carriers [8].

2.2.2 CO_2-eq emissions

CO_2-eq is a metric measure used to compare the global-warming potential (GWP) of various greenhouse gases (GHG). Each greenhouse gas has a different GWP and persists for a different length of time in the atmosphere. In this case, CO_2-eq factor is related with the greenhouse emissions and impact in the environment of energy carriers, including not only CO_2 gases, but also others such as CH_4, N_2O, VOCs, etc. After the conversion, every energy carrier used in the building will have the same unit of impact and can therefore be compared. How to calculate indirect greenhouse gas emissions caused by energy use in buildings is described in the standard NS EN 15603 [10].

The table 2.1 includes total and non-renewable primary energy factors and CO_2-eq factors. It is divided in those energy carriers used during the project. Even if these factors are very important parameters for the NZEB balance, there are no official factors yet in Norway. In the calculations, total primary energy and CO2-eq will be used as weighting factors. This project applies the values of the table below basically because they were used in the previous cost optimal methodology for residential buildings [54]. Primary energy factors are taken from the European standard of energy performance of buildings or prEN 15603. CO2-eq emission factors instead are recommended values by the ZEB centre in the proposed Norwegian ZEB definition. However, the European standard and the ZEB centre show conservative values for District heating, so the values chosen in this project are simply an assumption of low primary energy and CO_2 emissions. District heating should be analysed on the basis of the actual GHG emissions associated with its production, what is normally hard to indentify. For a more holistic approach, some primary energy conversion factors are collected in Appendix A.

Energy carrier	Total primary energy factors [kWh/kWh]	Non-renewable primary energy factor [kWh/kWh]	CO2 factor [g CO2/kWh]
District heating	**0,75**	**-**	**65**
Pellets	**0,20**	**-**	**7**
Electricity imported from the grid	**2,5**	**2,3**	**130**
Electricity imported from onsite	**1**	**0**	**-**
Electricity temporary exported and reimported later	**2**	**2**	**-**
Electricity exported to the grid	**1,6**	**1,6**	**-**

Table 2.1: Primary energy factors and CO_2-eq factors

2.2.3 Calculation of primary energy consumption and CO_2 emissions

According to EPBD recast and the European norm EN 15603:2008 the balance described in chapter 2.1 shall be based on delivered and exported energy. Moreover, to calculate the net delivered energy in order to measure the energy performance (delivered minus exported energy per energy carrier), the previously defined building system boundary has to be taken into account. For a better understanding, a building that complies with the net zero energy requirement will have a value of 0 kWh/(m^2year) of net delivered energy.

The figure 2.5 gives a first approach on how the energy use in buildings and how the net delivered energy should be calculated. First of all, the energy need of the building is estimated, which represents the energy needs for heating, cooling, ventilation, domestic hot water, lighting and appliances. Technical installations of a building aim to maintain indoor thermal conditions as well as provide necessary electrical energy for lighting and appliances. Even if low energy buildings have a tight isolation, there is still heat exchange through the building envelope that causes thermal losses throughout the year. In winter for example, the energy need for heating is caused by these heat losses, but it is also compensated by solar and internal heat gains. Building technical systems are in charge of supplying the energy needs for heating, cooling and electricity. Of course these systems, which provide thermal and electrical energy to the building, consume a part of the energy and have their corresponding efficiency characteristics. The energy used by building technical systems is delivered from the electrical grid, district heating and cooling network or from renewable and non-renewable fuels.

Moreover, the renewable energy produced on-site, for example produced by photovoltaics or wind turbines, is not considered as part of delivered energy. On-site renewable energy production systems can provide energy to building technical systems, thus reducing the amount of delivered energy use in the building, or can directly export the energy to networks, normally to the electrical grid.

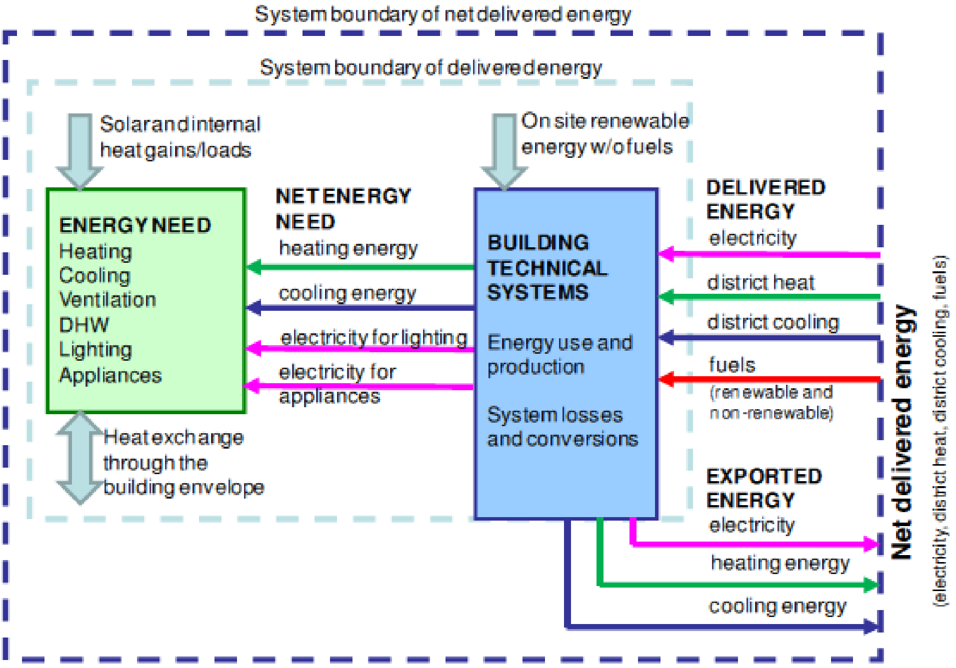


Figure 2.5: Schematic representation of the connection between energy need, energy use, delivered energy and exported energy

As it is well shown in the following equations, primary energy consumption as well as CO_2 emissions are calculated from delivered and exported energy previously multiplied with the appropriate weighting factors per energy carrier.

Annual primary energy consumption

EN 15603 [10] states that, per energy carrier, the exported energy can be subtracted from the imported one to calculate the primary energy demand:

$$E_p = \sum_i (E_{del,i} * f_{p,exp,i}) - \sum_i (E_{exp,i} * f_{p,exp,i}) \qquad \text{(Equation 2.16)}$$

Where

E_P means annual primary energy consumption, in kWh.

$E_{del,i}$ means annual delivered energy from energy carrier i, in kWh.

$E_{exp,i}$ means annual exported energy from energy carrier i, in kWh.

$f_{P,del,i}$ is the primary energy factor for the delivered energy carrier i, in kWh/kWh.

$f_{P,exp,i}$ is the primary energy factor for the exported energy carrier i, in kWh/kWh.

Annual CO_2 emissions

Following the same reasoning for the CO_2-eq emission calculation, the annual CO_2-eq emissions can be calculated like:

$$m_{CO2} = \sum_i (E_{del,i} * k_{del,i}) - \sum_i (E_{exp,i} * k_{exp,i}) \qquad \text{(Equation 2.17)}$$

Where

m_{CO2} means annual CO_2 emissions, in Kg.

$E_{del,i}$ means annual delivered energy from energy carrier i, in kWh.

$E_{exp,i}$ means annual exported energy from energy carrier i, in kWh.

$k_{P,del,i}$ is the CO_2-eq factor for the delivered energy carrier i, in kWh/kWh.

$k_{P,exp,i}$ is the CO_2-eq factor for the exported energy carrier i, in kWh/kWh.

2.3 Norwegian NZEB definition

During the last years, the term zero energy building (ZEB) has been used continuously without a clear definition in place. In the EPBD it is established that Member States have to include in their national plans a detailed application in practice of the definition of nearly zero-energy buildings, reflecting their national, regional or local conditions. National guidelines are needed to increase the number of high energy performance buildings, which should be supported by a consistent definition. Each country should define its own definition in accordance with their specific conditions, political and economic targets [8].

Different research centres have tried to address issues related to the ZEB definition in their own countries. In Norway, the ZEB centre has managed to present a Norwegian zero emission building definition in the Passivhus Norden 2013 conference [15]. The current definition is based on nine criteria's:

2.3.1 Ambition level

It is possible to distinguish four different ambition levels for ZEBs, explained in detail in Appendix B. The Norwegian Research Centre of Zero Emission Buildings (ZEB) is pursuing the most ambitious level: "buildings with zero emissions of greenhouse gases related to their production, operation and demolition". This level is known as ZEB-COM, where construction, operation and embodied emissions during the building life (including demolition) are considered. Figure 2.6 shows how different levels introduce new items of the building's lifecycle. For this project a ZEB-O level is considered, so the entire energy supply for building operation should be based on renewable energy sources with zero net emissions of climate gases during the year.

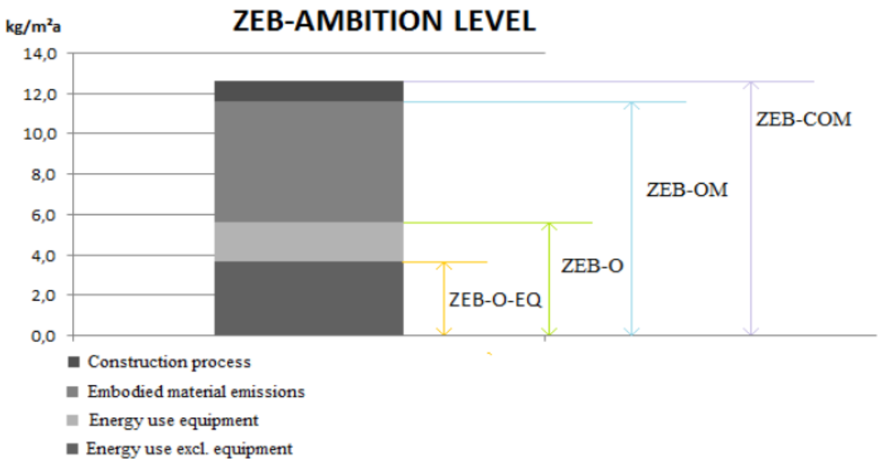


Figure 2.6: Different ZEB ambition levels in the current ZEB-definition [16]

2.3.2 Rules for calculation

Specific rules have to be followed when calculating the energy use and CO_2 emissions in a Norwegian building. Calculations should be performed with validated methods and according to NS 3031, the official Norwegian standard for energy performance. Institutionally accepted dynamic simulation software, like the one used during this project (IDA-ICE), should preferably be the tool for these calculations. Both standards NS 3700 and NS 3701 can be used to define the values for installations in the models. Simulations shall use local climate conditions, like the Oslo climate for this project, and a calculation period of one year.

2.3.3 System boundaries

Defining the boundaries in the system is like in any calculation, one of the most important steps. Only the energy flows crossing the building system boundary will be considered. The physical boundary will distinguish between 'on-site' and 'off-site' generation systems. In the NZEB balance, the renewable energy production systems shall be 'on-site' systems, while the heating system can be both. The balance boundary is the one that defines which energy uses (heating, cooling, DHW, lighting) are taken into account. A combination of both boundaries will be the building system boundary.

2.3.4 Weighting factors

The ZEB centre is focused in CO_2-eq emission factors in a life cycle perspective because the Norwegian government has not developed yet primary energy factors. The current CO_2-eq electricity factor is based on the average emission per kWh produced electricity in Europe. The scenario below assumes that the electricity supply in Europe will be carbon neutral in 2055. If that linear scenario is assumed, the average emission factor is 132 grams ofCO2-eq/kWh.

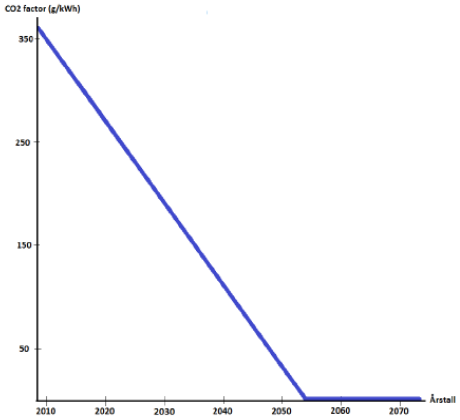


Figure 2.7: Assumed development for the average CO_2-eq factor for electricity from 2010 towards 2055

2.3.5 Energy quality

Two main types of energy are used to satisfy the energy demand of the building: electricity and heat (heated water). Electricity is a high quality energy that can be used for most of the energy needs of the building. When using high voltage, it is possible to transport electricity long distances with relatively low losses. On the other hand, heated water is a lower quality energy source dependent on the water temperature and it is only used to cover space heating and domestic hot water demand. Therefore, a ZEB will cover its entire energy demand with both electricity and heat, while the exported energy will normally be electricity. It is also accepted to connect the heating system with the district heating network to export the excess heat energy, but limited so that the exported energy cannot exceed imported energy.

2.3.6 Energy efficiency

When constructing a zero emission building different kind of measures should be taken into account for the reduction of energy use and emissions. Thus, if a constructor wants to achieve a ZEB range for the building, the application of passive and active measures will be necessary to achieve the required consumption values. As explained before in chapter 1.2, in Norway there are two important standards on energy efficiency in low energy buildings: NS 3700 for residential buildings and NS 3701 for non-residential buildings. ZEBs will therefore use passive house minimum requirements (windows, doors, thermal bridges and ventilation). These standards also settle their maximum allowed heating, cooling and artificial lighting demand to ensure that the building minimizes energy consumption.

2.3.7 Mismatch

NZEBs have different abilities to match the load and accomplish a beneficial energy exchange with the grid. There is a mismatch between energy production and demand throughout the entire year, and therefore the system has to be connected to the grid, thus the grid can supply energy to the building during low production periods and vice versa. For a better understanding of the energy balance and the mismatch phenomenon, it is recommended to make an analysis for each project using the mismatch factors and indicators explained in [15]. The figure 2.8 shows that a ZEB, with a normal ‘on-site’ PV generation system, will present a low temporal correlation between load and generation. In winter the load is higher due to the huge heating consumption, whereas the PV generates more in summer. The load matching is an example of indicator for an energy balance analysis.

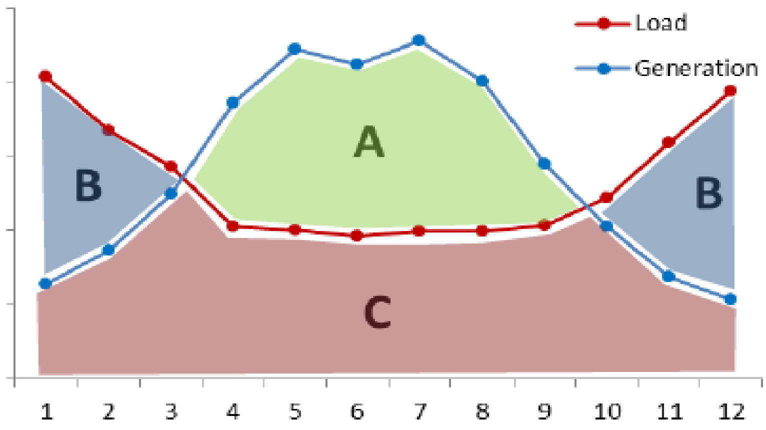


Figure 2.8: Monthly graphs of electricity load and generation [15]

2.3.8 Indoor climate

A zero emission building should also comply with certain requirements regarding the indoor quality and thermal comfort inside the building. The current Norwegian building code (TEK10) specifies the indoor climate requirements. It defines maximum air speed, maximum operating temperature during summer and winter, maximum CO_2 levels and minimum daylight among others.

2.3.9 Measurements and Verification

To check that a building accomplishes with the NZEB definition described, it is necessary to carry out a measurement process. This is a verification process, where the building is monitored, to compare the designed and simulated design. Delivered and exported energy, energy use, renewable production on-site and indoor climate among other data should be monitored.

2.4 Cost optimal methodology

According to the EPBD, Member States have to "assure minimum energy performance requirements for buildings or building units with a view to achieving cost-optimal levels". A cost optimal level is defined as: "the energy performance level which leads to the lowest cost during the estimated economic lifecycle" [17]. In 2012, the European Commission established a comparative methodology framework and accompanying guidelines, [18] and [19] respectively, for calculating cost-optimal levels that would serve to supplement what the Directive 2010/31/EU (EPBD) proposed.

The guidelines [19] states: "The methodology specifies how to compare energy efficiency measures, measures incorporating renewable energy sources and packages of such measures in relation to their energy performance and the cost attributed to their implementation and how to apply these to selected reference buildings with the aim of identifying cost-optimal levels of minimum energy performance requirements".

Therefore, this methodology is a really useful calculation tool to compare different energy supply solutions and choose the most appropriate one from an economic point of view. This project aims to find the cost-optimal energy supply solution for an office building, which should not be mistaken for a cost-effective one. Cost-optimality and cost-effectiveness are related, but they are not the same, the first is the optimal case of the last. In the particular case of energy performance, a system is cost-effective if the cost of implementation to fulfil the minimum energy requirements is lower than the benefits that result. It can be said, related with the Net Present Value (NPV) concept used to analyze the profitability of an investment, which will be explained later, that the system will be cost-effective when NPV>0. As the figure 2.9 shows the cost-optimal value is the one that maximizes the NPV. Both measurements are based on a comparison between the costs and savings of the mentioned implementation.

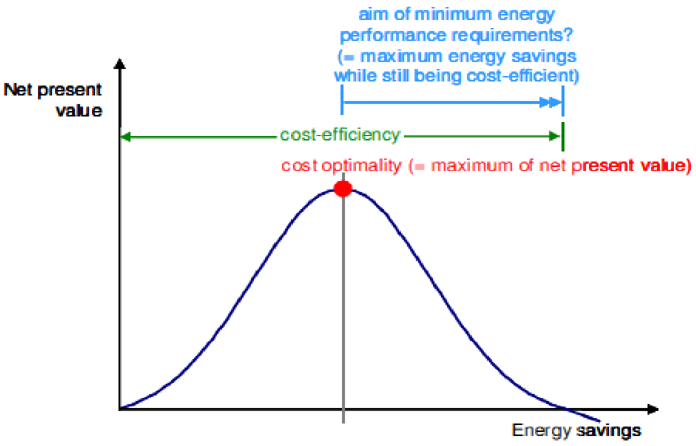


Figure 2.9: Scheme presenting cost-optimality and cost-efficiency [17]

2.4.1 Possible perspectives

Cost-optimality can be analyzed from different perspectives, each of them give usually a different result. The two main perspectives to perform the calculations are:

- Macroeconomic perspective: The analysis is carried out from a societal point of view. This approach considers all the cost and benefits that will affect the society (externalities), including the damage to the climate associated to greenhouse gas emissions. Thus, it includes the costs of CO_2 emissions and ignores taxes and subsides. Calculations in a macroeconomic perspective make it easier to compare different energy performance measures that reduce energy use and CO_2 emissions in a building. A comparison between supply technologies can be also done considering the same two factors.

- Financial or microeconomic perspective: Calculations are done at a private or end-user level. This approach considers the immediate costs and benefits that are faced by the investor, including possible taxes and ideally also subsides.

2.4.2 Calculation of global costs

The cost-optimal methodology described in the EU regulation [18] is based on global costs calculations. Actually, the term global cost corresponds to what is normally called "lifecycle cost analysis" (LCCA). This is a method that can be used to compare alternative building systems with different investment and operating costs. A global cost calculation results in the net present value (NPV) of the costs incurred during the defined calculation period. When dealing with long lifetime systems, such as energy supply technologies, all future cash flows need to be discounted back to today in order to calculate the net present value of each solution. The advantage of the global cost method in compared with others, is that it allows the use of a uniform calculation period.

In accordance with the European regulation, global costs calculations shall include the initial investment, the sum of every year's annual costs and disposal costs as well as costs of greenhouse gas emissions in the case of a macroeconomic analysis. In figure 2.10 it can be seen in detail all the cost parameters that should be considered during the calculations. Disposal costs only have to be included if it is necessary. Energy produced by renewable energy sources on-site, like a PV system, should be regarded as earnings in the financial calculation [14]. It should be noted that this methodology as stated in the Regulation does not include other costs than energy, so it is not considering a complete life cycle assessment.

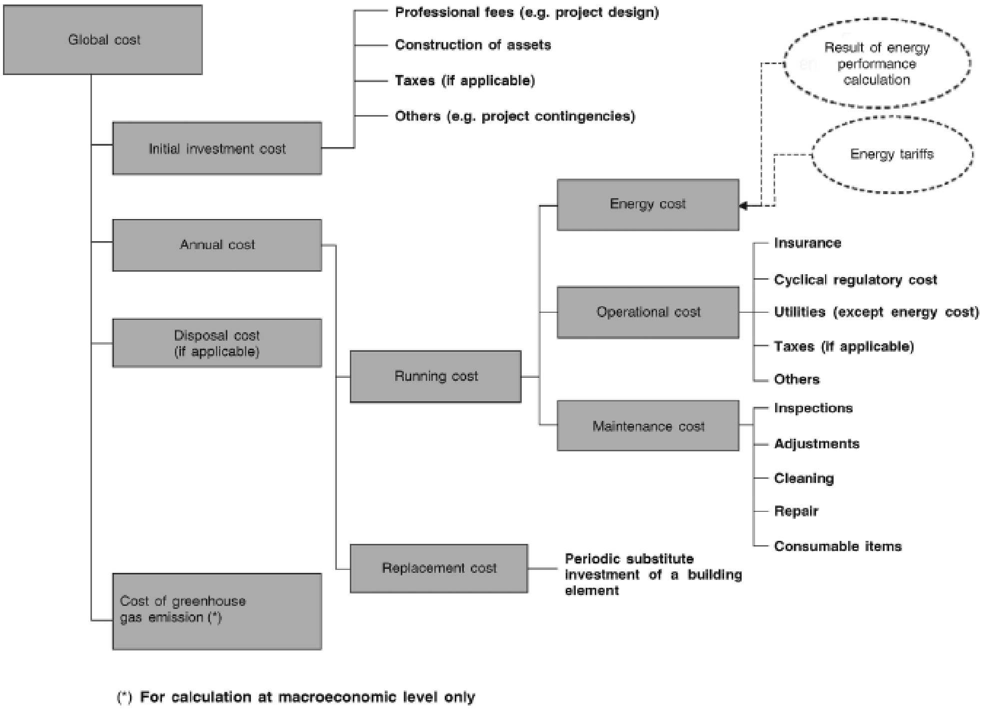


Figure 2.10: Cost categorisation according to the framework methodology [19]

Discount rate

The discount rate refers to the interest rate used in discounted cash flow analysis to determine the present value of future cash flows. It takes into account the time value of the money (how the value of the money change from one year to the other) and the uncertainty; the higher the uncertainty is in the future cash flow, the higher the discount rate will be. Each country has its own discount rate, established after performing the corresponding sensitivity analysis. The real discount rate will be used as a fixed value during calculations removing the effects of price changes over time, in other words, excluding the inflation. The following equations have been adapted from [14]:

$$Rr = \frac{R - Ri}{1 + Ri/100} \quad [\%] \qquad \text{(Equation 2.18)}$$

Where

R_r is the real interest rate

R is the nominal interest rate

R_i is the inflation rate

However for low levels of inflation we can use the much simpler Fisher equation to calculate the real interest rate.

$$Rr = R - Ri \quad [\%] \qquad \text{(Equation 2.19)}$$

Discount factor

To make the discount rate applicable, usually a discount factor will have to be derived that can be used in the global cost calculation. The discount factor for each year can be calculated as:

$$Rd(p) = \left(\frac{1}{1+Rr/100}\right)^{p} \quad [-] \qquad \text{(Equation 2.20)}$$

Where

p is the number of years after the starting period.

Global costs for a financial calculation

To calculate global costs in a financial or microeconomic perspective, the relevant prices to be taken into account are the prices paid by the customer including all applicable taxes, like the tax on the purchase price called value added tax (VAT), and possible charges. Ideally available subsides for building elements as well as existing subsides for energy prices can be included. However, depending on the country where the analysis is performed, subsides can be left aside. Finally, global cost shall be calculated by summing the different types of costs and applying to these the discount rate by means of a discount factor to express them in terms of value in the starting year, plus the discounted residual value as follows [18]:

$$Cg(\tau) = C_I + \sum_j \left[\sum_{i=1}^{\tau} \left(Ca,i(j)\ x\ Rd(i) \right) - Vf,\tau(j) \right] \quad [\text{NOK}] \qquad \text{(Equation 2.21)}$$

Where

τ means the calculation period.

$Cg(\tau)$ means global cost (referred to starting year τ_0) over the calculation period.

C_I means initial investment costs for measure or set of measures j.

$Ca,i(j)$ means annual cost at year I for component j.

$Vf,\tau(j)$ means residual value of measure or set of measures j at the end of the calculation period (discounted to the starting year)

$Rd(i)$ means discount factor for year i based on discount R_R.

Global costs for a macroeconomic calculation

When determining the global cost in a macroeconomic perspective, all the prices should be taken into account excluding all applicable taxes, VAT, charges and subsides. In addition, costs of green house gas emissions have to be included so that the final expression is [18]:

$$Cg(\tau) = C_I + \sum_j [\sum_{i=1}^{\tau} (Ca,i(j)\ x\ Rd(i) + Cc,i(j)) - Vf,\tau(j)] \qquad [\text{NOK}]$$

(Equation 2.22)

Where

$Cc,i(j)$ means carbon cost for measure or set of measures j during year i.

Residual value

The estimated lifecycle of building elements in the global cost calculation can either be longer or shorter than the calculation period. If the estimated lifecycle is shorter than the calculation period, which is the normal case in energy supply technologies, the building element should be replaced with an additional investment, called replacement cost. As it can be seen in the figure 2.11, a new depreciation period will start. In the particular case of the image below, when the period is finished the residual value will be half of the investment cost. At the end of the calculation, the residual value is referred back to the starting year and discounted as a negative investment.

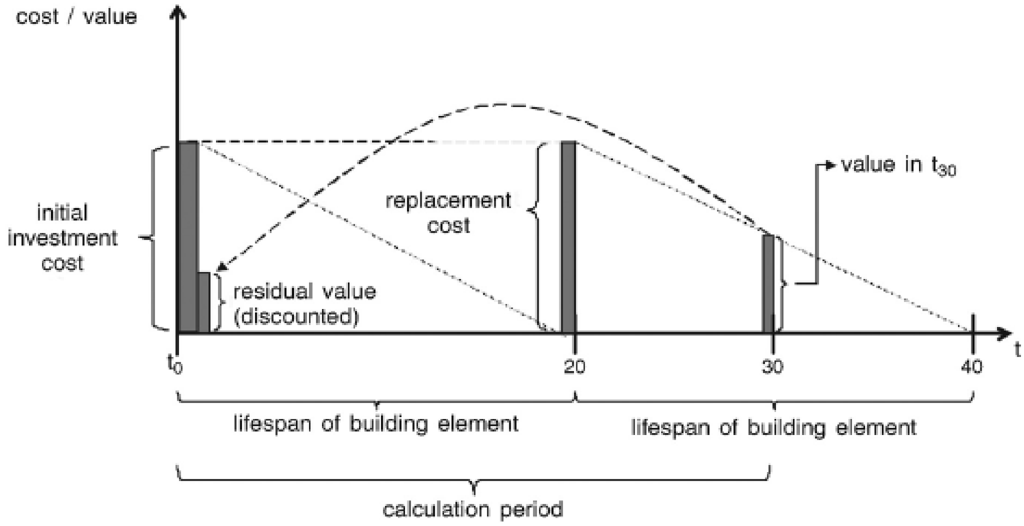


Figure 2.11: Illustration of the residual value of a building element which has a shorter lifetime than the calculation period

The residual value of a building element is determined by straight-line depreciation of the initial investment cost or the last replacement cost until the end of the calculation period [5]. The residual value can be calculated as follows [14]:

$$Vf,\tau(j) = Vo(j)\ x\ (1 + \frac{Rp}{100})^{n_\tau(j) x \tau_n(j)}\ x\ \left[\frac{(n_\tau(j)+1) x\ \tau_n(j) - \tau}{\tau_n(j)}\right] x\ Rd(\tau) \qquad [\text{NOK}]$$

(Equation 2.23)

Where

n(j) represents the total number of replacements of component j throughout the calculation period.

$Rd(\tau)$ is the discount factor at the end of the calculation period.

$Vo(j)\ x\ (1+\frac{Rp}{100})^{n_{\tau}(j) x \tau_{n}(j)}$ represents the last replacement cost, when taking into account the price development for the product, using R_p inflation rate.

$\left[\frac{(n_{\tau}(j)+1) x\ \tau_{n}(j)-\tau}{\tau_{n}(j)}\right]$ is the straight-line depreciation of the last replacement cost.

2.5 Energy supply systems

There is an existing debate nowadays over the choice between centralized or distributed energy supply system for buildings, and which one has a greater benefit in the society. A centralized system is the production of energy by a central plant in an industrial area and then distributed to the customer, while a distributed energy system refers to the variety of small technologies placed near the point of energy consumption. Both of them present a number of advantages and disadvantages. The current energy distribution infrastructure is developed enough to offer the possibility of relatively low losses during the distribution. This together with a higher efficiency and reliability in a plant production are the strengths of a centralized supply system [20]. However, as mentioned in the part about the building's system boundary, a ZEB shall use on-site energy production based on renewable energies. Therefore, zero emission buildings will be more focused in distributed systems with local production. This is mainly because decentralized systems have a lower carbon footprint. Anyway, even if ZEBs need to have on-site energy production, when choosing the heating supply system also off-site systems can be used. The best example of this, is a district heating network as heat energy supplier, commonly used in Nordic countries like Norway.

The main purpose of an energy supply technology is to convert primary energy into another energy carrier more appropriate for demand and distribution, in buildings normally heat and electricity. There are a number of available technologies in the actual market that can be used for the energy supply of a ZEB, as it can be seen in the table 2.2. All of them should be considered in a real study, taking into account the maturity, investment, complexity and potential of each system. However, this project only aims to explain the selection process and not to perform a real market analysis. Nevertheless most of these systems will be included, among others: District Heating (DH), Air Source Heat Pump (ASHP), Ground Source Heat Pump (GSHP), Electric Boiler (EB), Biomass Boiler (BB), Combined Heat and Power (CHP), Solar Thermal (ST) and Photovoltaic (PV).

Heat supply technologies	**HP**	**Heat Pumps**
	BB	Biomass Boiler
	DH	District Heating
	ST	Solar Thermal
Electricity production technologies	PV	Photovoltaic
	MW	Micro Wind turbine
Combined production technologies	CHP	Combined Heat and Power
	PVT	Photovoltaic, thermal hybrid solar collector
	FC	Fuel Cell

Table 2.2: Available technologies for renewable supply to buildings [20]

2.5.1 District heating

District heating can be defined as a system which distributes hot water from a heat energy production plant to the users. The primary energy is transformed into thermal heat or cooling in the production plant and later is distributed to different customers through an insulated pipes network. A district heating distribution system is formed by a supply and a return pipe where water flows with temperatures between 40º and 120º [21]. One of the most important parameters to ensure a correct flow of water in the pipelines is the pressure drop; the system should be pressurized according to the pipe length [22]. It is remarkable that the use of DH requires that the building has previously installed a waterborne heat distribution system as well as a substation. The place where the heat is delivered to the customer is called customer substation. A substation is equipped with different kind of measuring devices, what makes easier the inspection and maintenance of the system inside a building. The connection between pipeline and substation can be direct or indirect. In the indirect one, usually used in Norway, the connection is made through heat exchangers. The figure 2.12 shows a simplification of the distribution system with a plant and four customer substations.

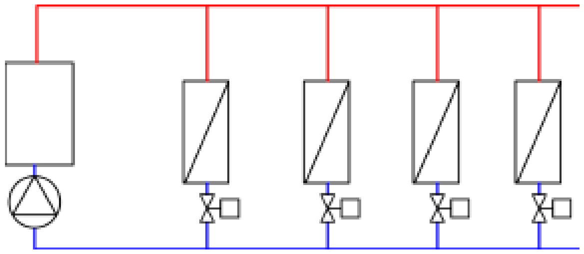


Figure 2.12: District heating distribution system [10]

One of the greatest advantages of DH is its flexibility in the production system. The plant is usually a CHP system, a Rankine or Brayton cycle which uses biomass, bio fuel, natural gas, oil or coil for the combustion in the boiler [20]. Another advantage is the possibility of using waste heat from near industries or incineration processes and geothermal energy directly delivered for the heat production. Depending on the production method it can be seen as a complete environmental friendly energy supply technology. Furthermore, the energy output of this kind of systems is also flexible because the CHP machine can deliver heating supply, cooling supply and electricity. Looking to the system’s efficiency, district heating is characterized by losses not only in the energy transformation process, but also during the distribution in the piping network and inside the building. The design of the piping system is a crucial factor in the total efficiency value.

District heating is well known, especially in Nordic countries, and technologically enough developed, thus it has become an interesting option for the heat supply of buildings. In addition, it is facing a continuous development in system design as well as improvements in the piping network and customer substations [20]. On the other hand, this technology is not available everywhere due to the complexity and time length of the network construction and development around a population area. It is normally promoted in areas with a high consumer density in order to afford the high investment that the construction implies. In any case, since the EPBD recast suggested that, if available, district heating should be considered to the detriment of common electrical heating, since DH has a great potential for extension in the future.

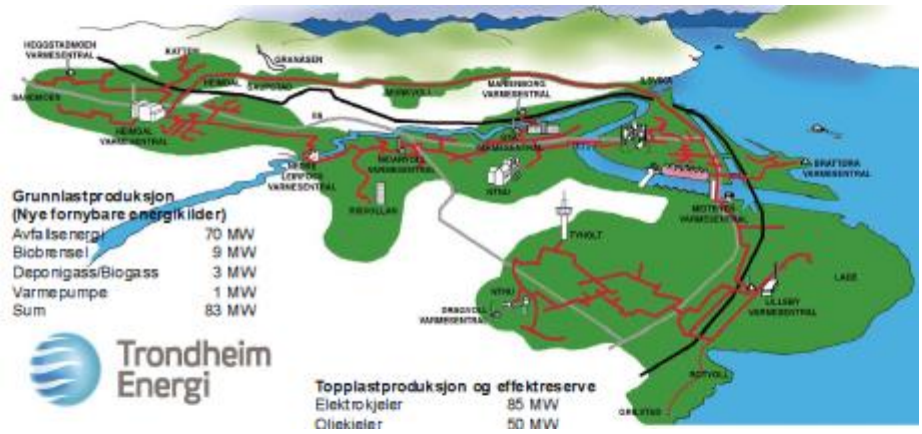


Figure 2.13: District heating network in Trondheim [22]

2.5.2 Heat pumps

Heat pumps are devices able to reverse the natural flow of heat, allowing a heat flow from a colder heat source to a warmer heat sink. They can transfer heat from different heat sources such as air, ground (rock, soil) or water to buildings or industrial applications [20]. Currently it is also possible to find reversible heat pumps transferring heat in the opposite direction, used for cooling purposes. There are two main types of heat pump operations, one based on the vapour compression cycle and the other on the absorption cycle. The vapour compression cycle heat pump is the more commonly utilized system that consists of an evaporator, compressor with electromotor, condenser and expansion valve connected by a closed pipe system with a circulating working fluid. The working fluid experiences changes of state in a continuous cyclic process, transferring in that process energy from the heat source to the heating system.

As mentioned before, heat pumps can be reversed for air-conditioning applications. Besides, they also have potential for free-cooling, which will be the preferred way of operation when the building has to be cooled down. As general rule, a heat pump design will try to take maximum advantage of its free-cooling capacity and use an additional chiller to satisfy the remaining demand. Reversible or not, the coefficient of performance (COP) is the most important factor when defining heat pump parameters. It is presented in the equation below as like the amount of heat obtained in the condenser divided by the electrical power used in the compressor. There is also a relation between the COP for heat pump (HP) and refrigeration system (REF) [23]:

$$COP_{HP} = \frac{Q_C}{W} \qquad COP_{REF} = \frac{Q_E}{W} \qquad COP_{HP} = COP_{REF} + 1 \quad \text{(when } \xi = 0\text{)}$$

(Equation 2.24 / 2.25 / 2.26)

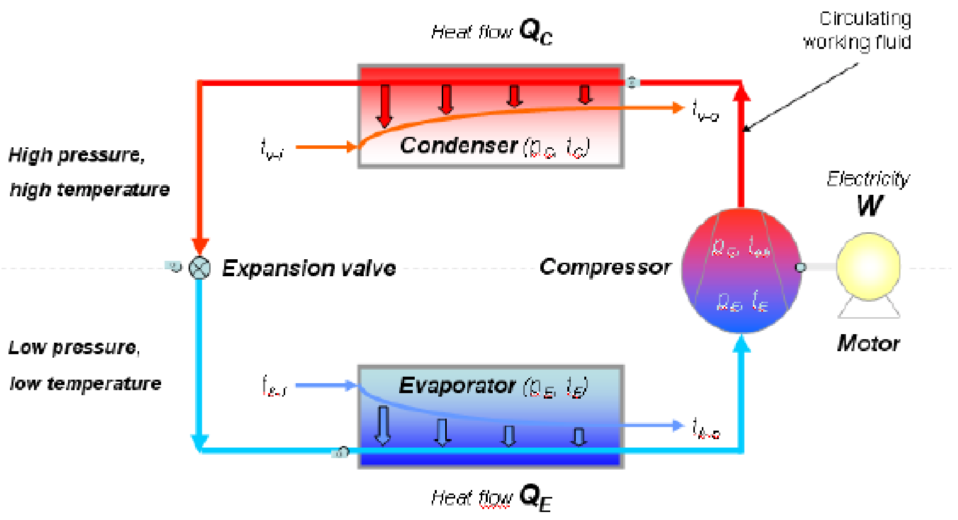


Figure 2.14: Heat pump [22]

Heat pumps can be classified according to the heat source used for energy extraction. In this project ambient air and ground source heat pumps will be simulated. Ambient air is the most used heat source; mainly because it is available everywhere and because the heat pump installation requires a lower investment cost. However, the use of outdoor air can present some problems in the heat pump performance due to temperature fluctuations during the year, for that reason it is preferably used in climates with long and mild winter [24]. Ground source heat pumps on the other hand, have higher and more stable source temperatures. For the same reason, they are also better systems for free-cooling. In a ground source heat pump the pipes are vertically or horizontally positioned in the soil, in deep vertical boreholes or buried in horizontal direction [20]. Vertical boreholes, which work as heat exchangers, usually have 80 to 300 metres depth. When designing a borehole system, holes distance and configuration are important parameters to take into account in order to avoid interaction between them. Especially, digging deep borehole systems can lead to important investment costs, but also a better heat pump performance.

2.5.3 Boilers

A boiler is a closed vessel in which water is heated. This device can be powered with different energy sources, such as electricity, coil, wood or natural gas. Two main types of boilers will be used as building energy supplies in this study: electric steam boiler and biomass boiler.

Electric steam boilers are simple machines that convert electrical energy fed from the grid into thermal energy. A typical electric boiler heats the water with a number of immersion heaters, and then, that water will be used for heating purposes in the HVAC system. They have excellent part load efficiency, for that reason they are mainly utilised as peak heating systems. These energy systems obtain their entire energy need from the electrical grid, thus depending on the electricity source they can be cheap as well as an environmentally friendly choice.

A biomass boiler is a low-emission heat supply technology that uses solid or fluid biomass as energy source. Biomass means organic material derived from plants and animal residues that react with oxygen in combustion to release heat. Apart from plant material, the term biomass also includes organic waste from industry such as forestry residue or wood chippings. There are mainly three types of boilers available for heating purposes: pellet boilers, wood chips boilers and biogas boilers. Pellets, compressed dry sawdust, systems have been successful technologies supplying heat to high thermal mass structures, even though wood pellet production is still more expensive than the others. Wood chips are the less expensive fuel and more energy efficient, but they are only available for large systems or industrial plants. Biogas boilers use gas originated from organic matter and can be produced from raw materials such as waste. In either case, biomass boilers are an efficient heat production technology with a very low environmental impact as an advantage; they are considered renewable energy systems. However, biomass fuelled systems are not the most effective technology during low load periods, so they are normally installed with a complementary heat source for part load, such as an electric boiler [20].

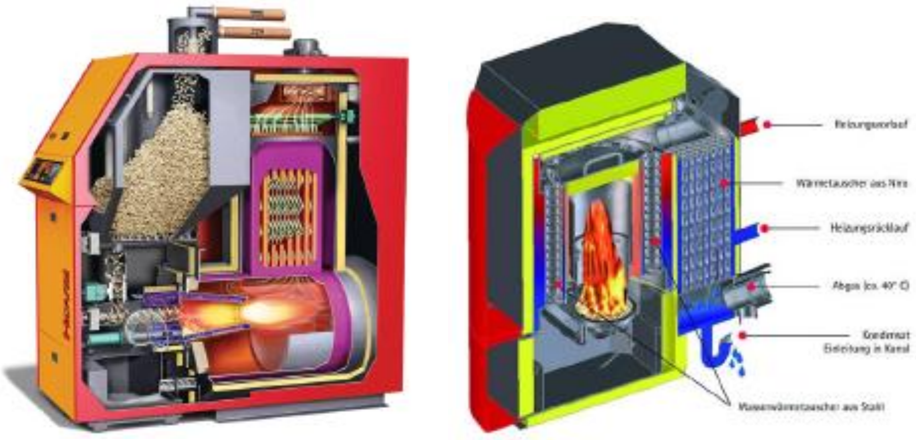


Figure 2.15: Wood pellet boilers [20]

2.5.4 Combined Heat and Power

Cogeneration or combined heat and power (CHP) is a system that generates both electricity and useful heat from the same energy carrier. A CHP for an energy plant is, as mentioned before, normally based on a Rankine, Brayton or Stirling cycles. The difference with a conventional power plant is that this technology captures the excess heat produced in the cycle, which otherwise would be wasted. Although it is a well developed system in large scale plant production, small scale CHPs are still an emerging technology. A micro-CHP or residential cogeneration, normally installed in the building's basement, is the system that a zero emission building requires to produce heat and electricity.

A CHP has two different efficiencies, one for the electrical generation and the other for heat generation. The electrical efficiency for different types of micro CHPs is around 15-40 %, while they have a higher thermal efficiency about 40-70%. Large CHP units are generally more efficient than micro CHPs, simply due to their higher scale. Either of them uses the equations to measure the total efficiency [20]:

$$\eta_{tot} = \frac{P_{el}+Q_{th}}{B} \qquad \eta_{el} = \frac{P_{el}}{B} \qquad \eta_{th} = \frac{Q_{th}}{B} \qquad \text{(Equation 2.27 / 2.28 / 2.29)}$$

Total efficiency Electrical efficiency Thermal efficiency

Where P_{el} refers to useful electrical energy, Q_{th} stands for useful heat and B is the energy fuel source used for the combustion.

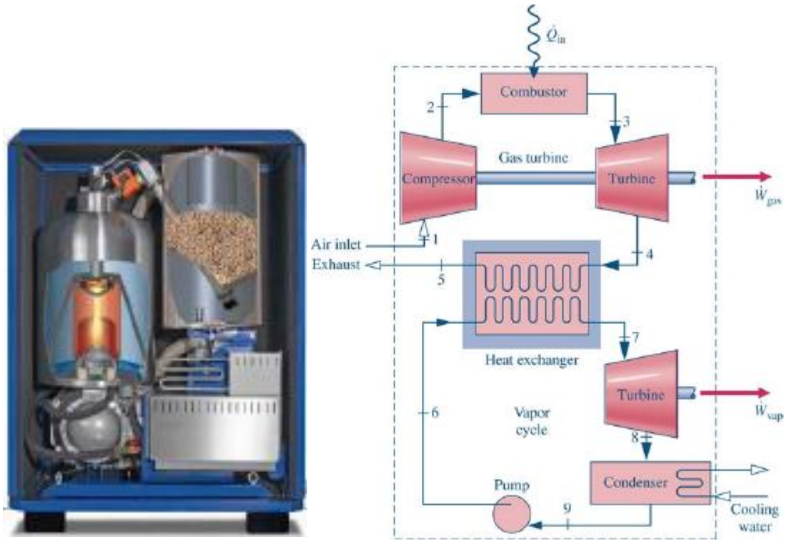


Figure 2.16: In the left a commercialized Stirling unit. In the right a combined CHP cycle.

According to [20], micro-CHPs are not common yet in large buildings with simultaneous demand of heat and electricity, however they will be considered in this study due to their future potential. As an example, biomass CHPs, which function by producing steam and passing the combustion gasses through a steam boiler, have already been commercialized, although they are under development.

2.5.3 Solar thermal collectors

Solar thermal collectors are devices that capture the incoming solar radiation, convert it into heat energy, and transfer that energy to heat up the water flowing through the collector. The energy collected is delivered to the building's heating system for a direct consumption or to the storage tank from which it can be drawn for use during night and cloudy days [25]. This is an important factor in Norway where weather conditions are only favourable for solar interception during summer months. That means that the seasonal thermal storage plays an important role, making it possible to shift the supply into demand periods. As it can be seen in figure 2.17, a complete system consists on solar collectors installed in the building envelope, storage tank, pipes, pump and controller. The controller or control unit is also a necessary device to ensure an efficient control of the flowing water in the piping system.

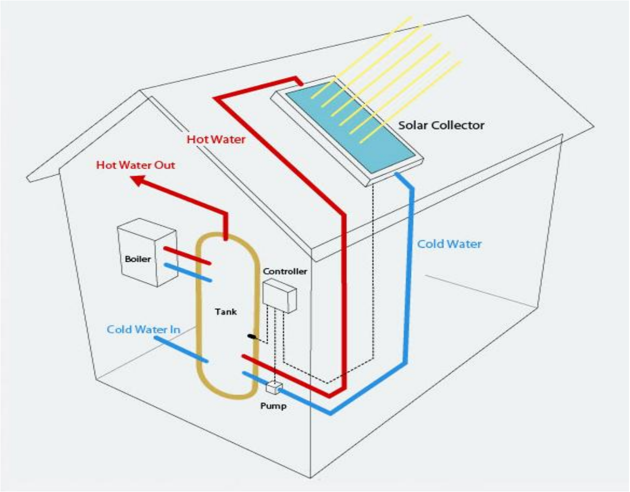


Figure 2.17: Solar thermal system

There are basically two types of solar collectors: non-concentrating or stationary and concentrating. A stationary model has the same area for solar interception and absorption, while a concentrating collector has a concave reflecting area that receives solar radiation and focuses the sun's beam to a smaller absorption surface [20]. Nevertheless, the second one has not been yet integrate in buildings and is mainly used for industrial activities. Consequently, this project will only consider different types of stationary collectors. With this in mind, it is possible to distinguish two types of systems: flat plate solar collectors (FPC) and vacuum tube collectors (ETC). FPC consists of a glass layer, absorber plate and attached tubes. In the ETC model the absorber material is in a glass tube in a vacuum state which minimizes heat losses in the collector. The absorber is the central piece of the system, a thin metal plate where the visible light is captured. Both types are presented in figure 2.18 below.

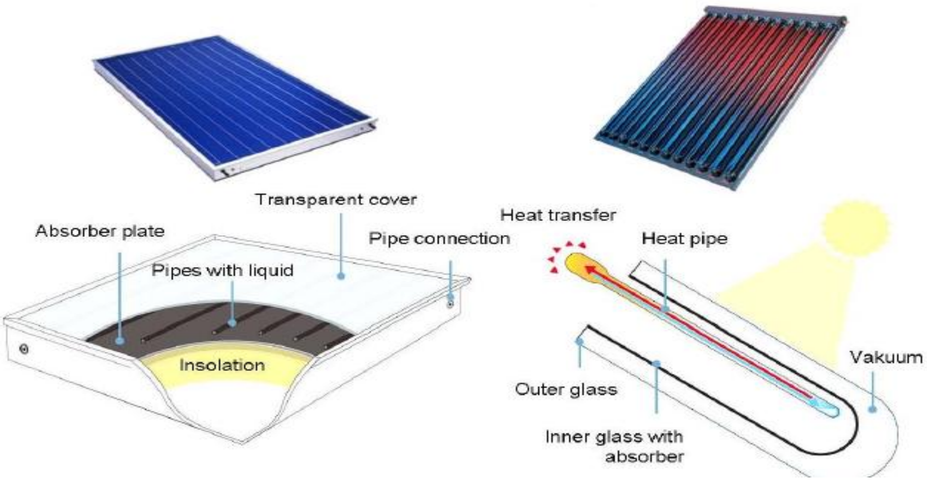


Figure 2.18: Two most used solar absorbers – Flat plate collector (FPC) on the left and evacuated tube collector (ETC) on the right, adapted from [20].

In a ST system the efficiency is defined as the amount of useful heat supplied from the collector divided by the amount of solar radiation that reaches the collector. It is highly related with the temperature difference between heat carrier and outside air, because low temperature distribution systems create a better performance, especially in cold climates like Norway [14].

$$\eta = Q_{useful} / (A.It) \qquad \text{(Equation 30)}$$

Solar thermal collectors are a developed technology, clean and can be supplied without any environmental pollution. Normally, they are installed in combination with an additional source of heat that will be used for covering the domestic hot water demands during the year. Solar thermal system combined with heat pumps is a system (SPH system) that it is in increasingly used in recent years. Coupling both energy supply technologies leads to higher seasonal performance factors (SPF) of the overall system than in traditional ones with separated heating systems. According to [26], solar thermal collectors can be used to complete the operation of a geothermal heat pump in three areas: preheating the domestic hot water, heating dwelling (directly or doping the temperature of the cooling source) and thermal recharging of the soil during excess solar production periods. Through the process of increasing the heat source temperature, heat pumps achieve benefits in its performance factor, while solar collector's degree of efficiency rises simultaneously due to lower return temperature. Additionally, the installation of a combined ST and HP system should not be decided considering only the efficiency, but also performing a study from an economic point of view.

2.5.4 Photovoltaics

Photovoltaics are semi-conductor type devices that generate electrical power converting solar radiation into direct current electricity. The name comes from what is called the photovoltaic effect, the process of converting sunlight photons into electrical voltage. A traditional solar cell is formed by a silicon p-n junction that is able to create an electric potential due to the movement of electrons [27]. When photons arrive to the upper layer of the cell, electrons are released to move from one layer to another and voltage is produced. Each solar cell produce a low amount of voltage, and by combining them in a module results in a higher voltage. Modules can be coupled either in series forming a string or in parallel forming an array, thus obtaining the desired electrical conditions, as shown in figure 2.19.

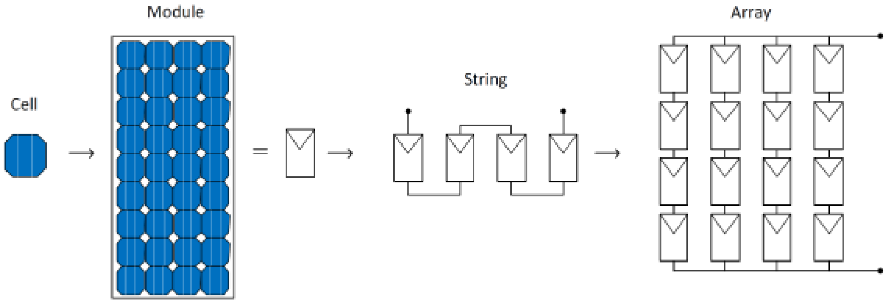


Figure 2.19: PV system configuration [28]

PV systems can be grid-connected or stand-alone (off-grid installation) systems. Either of the two types can be classified as BIPV whenever it is integrated into the building architecture and envelope. Building integrated photovoltaics (BIPV) normally replace a part of the building like roof, glazing or façade cladding. Otherwise, general systems are optimized for efficiency and simply mounted on the roof or façade [20]. ZEB buildings will only consider grid-connected system due to the necessary energy exchange with the grid.

In the image below a normal grid-connected system is illustrated. It consist of a number of PV modules, inverter, distribution boards (ACDB) connected with the building, meter and electrical substation. The inverter is responsible for converting the direct current electricity (DC) into alternating current electricity (AC), so that it can be compatible with the building's electrical installation. The substation is the union with the power grid, providing voltage changes to allow an electrical exchange with the building. Thanks to this installation, the building can have two parallel power supplies, one from the solar PV and other from the grid. A combined supply will cover the electrical needs of the building through the ACDB system.

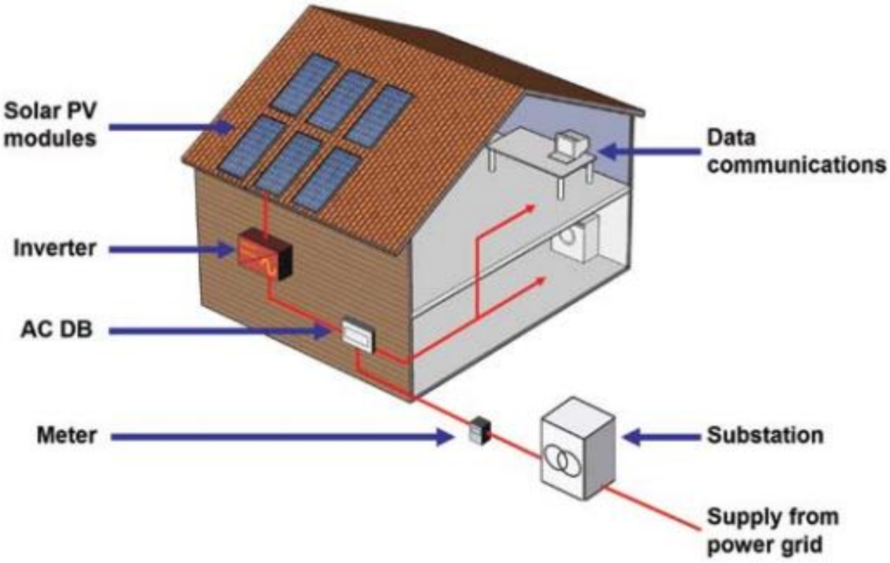


Figure 2.20: Grid connected solar PV system configuration [29]

The efficiency for conversion of solar radiation into electricity is greatly dependent on the type of cell that is being used. Nowadays, there is a large variety of cells (mono-crystalline, poly-crystalline silicon, flexible thin film, organic...) available in the market with different ranges of efficiency. Solar irradiance and temperature are important factors that influence the performance of the cell. Both are related with the geographical location where the PV system is going to be installed because of the sun’s conditions. Solar cells should try to collect as much solar radiation as possible for a better performance. To achieve that, modules have to be installed in the optimum tilt angle, which will depend on the geographical latitude of the location. The PV system roof disposition for a Norwegian climate will be discussed in later sections.

2.6 IDA-ICE

The software used for energy simulations in this project is called IDA-ICE. IDA Indoor Climate and Energy is a whole year detailed and dynamic multi-zone simulation application for the study of thermal indoor climate as well as energy consumption of an entire building [30]. The latest version IDA-ICE 4.6 has been used to define the building model and run the simulations of the building performance over a year. Multi-zone models can be created, defining each room of the building with different conditions. Besides, it gives the possibility to import to all common 2D and 3D CAD models used today in architecture. Thanks to the BIM extension, the user can work and simulate models generated by tools such as ArchiCAD, Revit, AutoCAD, MagiCAD and many others. Geometry can be also imported from SketchUp or other geometry tools.

Figure 2.21: IDA-ESBO logo

On the right side of the figure 2.22 there is a screenshot of the Early Stage Building Optimization (ESBO) model. ESBO plant is a new IDA-ICE user interface that simplifies early design stage building optimization. It allows the users to make variations in building's systems at an early stage with a minimum input, so for example the energy supply system can be changed defining only a few parameters. Therefore, in this project all the parameters of the energy supply technologies have been defined with IDA-ESBO. This program wizard includes a full range of renewable energy system models like heat pumps, boreholes, solar collectors, wind turbines, CHP, PV, etc. IDA-ICE can be used by engineers or system designers who are not experts in simulation methods, although there is also an advance level. Advanced users can build their own handling units, control systems and plants, as well as add new equation based models. Extension packages are also available for the software; they are normally useful for more advanced studies.

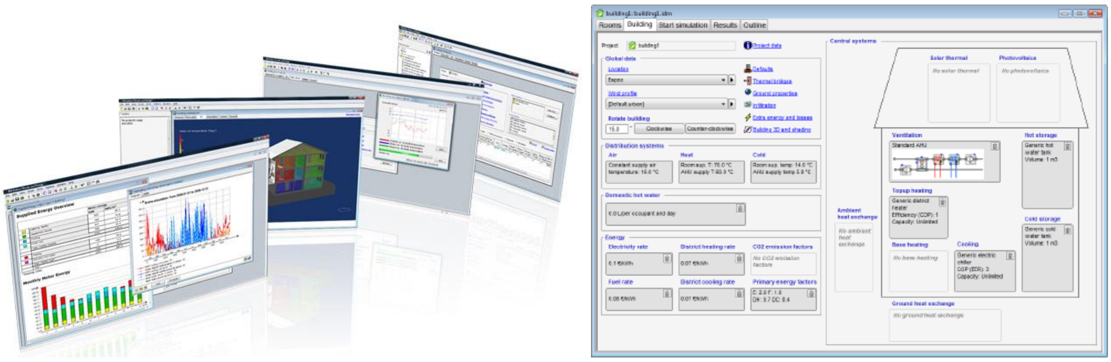


Figure 2.22: Screenshots from IDA-ICE [31]

Final results and output data can be exported to MS Excel and Word reports. This option facilitates the visualization of the necessary output data among all the other data that these kind of studies provide. Zone heat balances (including contributions from sun, occupants and light), air CO_2 and moisture levels, air temperatures, comfort indices, total energy costs, primary energy and CO_2 emissions are some of the possible outputs. The program gives comprehensive tables and graphs including all these parameters.

In recent years, IDA-ICE is gaining importance as energy simulation software among Norwegian researchers. The program gives optimum results for any kind of building performance studies. One of the most important reasons for the selection of IDA-ICE is its accuracy, as a dynamic simulation tool, in the calculations of cooling, heating, energy and air demand. Comparing with other major software tools like Energy+, ESP-r or TRNSYS, it offers a similar reliability. In fact, it is considered together with them one of the most appropriate and advance energy simulation software tools [32]. Although IDA-ICE needs certain level of expertise to understand correctly how it works, it is easy to unfold using it and it offers a friendly graphic interface. Apart from these, energy consultants and building contractors have start to show their interest in the program. Since this project aims to serve as a methodology for them, to help with the energy supply cost-optimal selection, it seems to be the best option to perform the calculations.

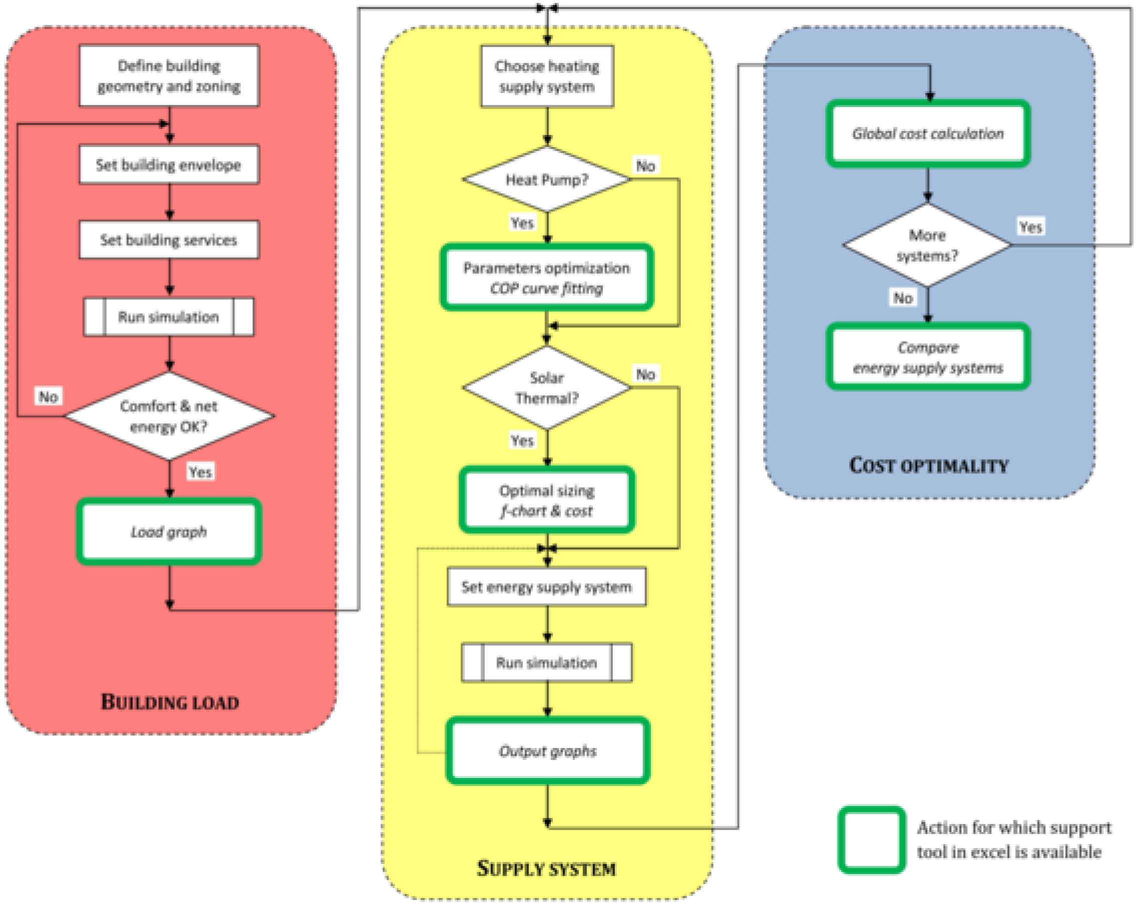
3. Approach

3.1 Methodology for early design phase analysis

This section aims to give an extended explanation about how to work with the methodology for early design phase analysis of energy supply systems in ZEBs. Making the decision regarding the energy supply system it is not an easy task; important factors have to be considered in order to be sure of selecting the best option for the building. To assure in-depth an accurate analysis, parameters such as building performance, energy system performance and economic factors have to be included.

The work presented follows a number of steps shown in the next page as a flow chart. To achieve an accurate final result the analysis should follow each step of the chart, from defining the concept office building and all its parameters in IDA-ICE, to make the cost optimal comparison of every system used at the end. For those boxes of the flow chart that are framed in green, a support calculation tool in Excel is available. These files have been set within the work [54], in which this Master Thesis takes part, to make possible calculations that are necessary and have not yet been developed by any program. Different programs have been designed in Visual Basic for Applications (VBA), which enables automating dynamic calculations in Microsoft applications. The required input data can be copied directly from IDA-ICE results and then pasted in the file itself; after that, there is a button to calculate the output data. These files make it much easier to perform the analysis for the energy supply selection, transforming it into an automatic process. In the following paragraphs the major steps of the methodology will be explained, paying special attention to how excel files should be used. It should be noted that this is the method followed to obtain the results of chapter 4 and 5.

The first step is defining the building geometry and the shape of each zone in IDA-ICE, well explained in chapter 3.2. Once the building model has been established, using any possible simplifications to reduce the simulation time length, it is the moment to define the internal parameters. Within them, it is possible to distinguish input data for building's envelope and technical installations. Aside from that, the most suitable weather file should be chosen. IDA-ICE only has a short list of available files, but it also offers the possibility of downloading and importing ASHRAE IWEC2 weather files from internet [32]. After setting all the parameters that can affect the building performance, the simulation characteristics should be established. It is recommended to select only those diagrams and graphs that will be further used; otherwise the software will take more time to simulate unnecessary information. The next step is to check the results obtained in terms of thermal comfort and net energy. If results show satisfactory values, they will be used to calculate the load graph; if not, building behaviour should be reviewed and some parameters changed.


Define building geometry and zoning
Set building envelope
Set building services
Run simulation
Comfort & net energy OK?
No
Yes
Load graph
BUILDING LOAD
Choose heating supply system
Heat Pump?
No
Yes
Parameters optimization
COP curve fitting
Solar Thermal?
No
Yes
Optimal sizing
f-chart & cost
Set energy supply system
Run simulation
Output graphs
SUPPLY SYSTEM
Global cost calculation
More systems?
Yes
No
Compare energy supply systems
COST OPTIMALITY
Action for which support tool in excel is available

3.1.1 Load graph

First of all, a building model with unlimited top heater and chiller should be simulated. This model will show which is the necessary heating and cooling demand for the building. After running the simulations and checking that all the requirements are satisfied, the load graph will be calculated using an excel file developed for this purpose. This file is prepared to give all the necessary information to know the quality of the building’s energy performance. Besides the load graph, each file provides other important graphs, output graphs in the flow chart, such as ZEB balances for primary energy and CO_2 factors, electricity month chart and graphs showing the performance of the selected energy supply system. Currently, there are as many files as possible base load technologies which supply heat to the building, thus each system has its own excel file where the capacity is drawn in respect to the load curve. If the energy supply system incorporates additional technologies like solar thermal collectors, other excel files have been developed with the aim of including the comparison between systems with and without ST, so the user can decide on the desirability of adding them.

Every file is based on a number of excel sheets where input data is written and others where output graphs described above are drawn. All the input data can be copied and pasted from output excel files provided by IDA-ICE. The necessary input data includes: weather data, energy delivered to the building and generated energy with the photovoltaic system among others. There is a simple program developed in Visual Basic for Applications (VBA) to perform some calculations in each file, thus results are automatically printed in different graphs.

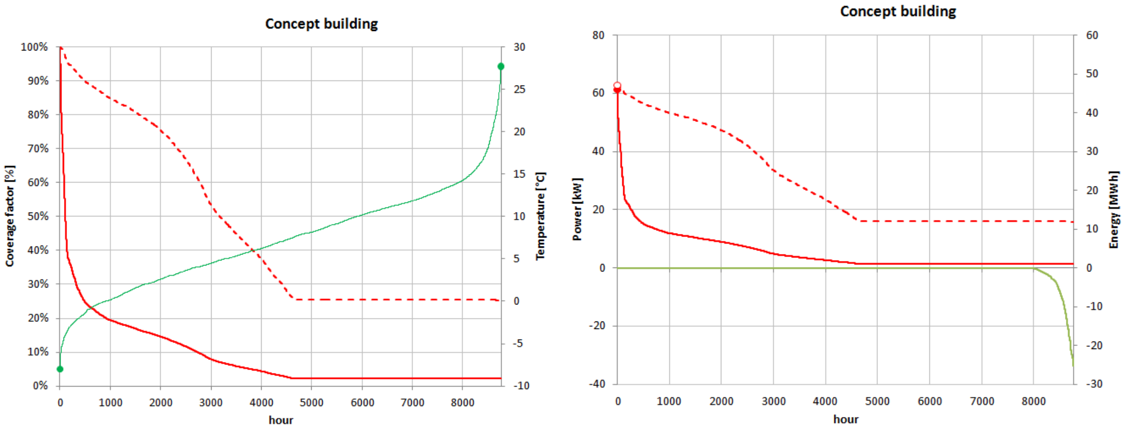


Figure 3.1: Load graph in % and kW

As mentioned before, the normal way of working is to define a plant with unlimited capacity to obtain the building load graph. After that, different energy supply systems will be dimensioned based on the calculated load graph. Normally, in a cost optimal analysis different base heating supply systems are compared. As the arrows of the flow chart show, the steps of selecting a supply system are repeated as many times as the number of technologies to compare. These steps include the solar thermal optimization, an excel file that serves as a tool to determine the optimal sizing area of ST for every based heating system. In addition, when the chosen system to analyze is a heat pump, the user should optimize first its IDA-ICE calibration parameters with another excel file developed for this purpose. Once ST optimal area and HP calibration parameters have been included in IDA-ICE, new results are again pasted in the excel file to obtain all the output graphs allowing to check final results.

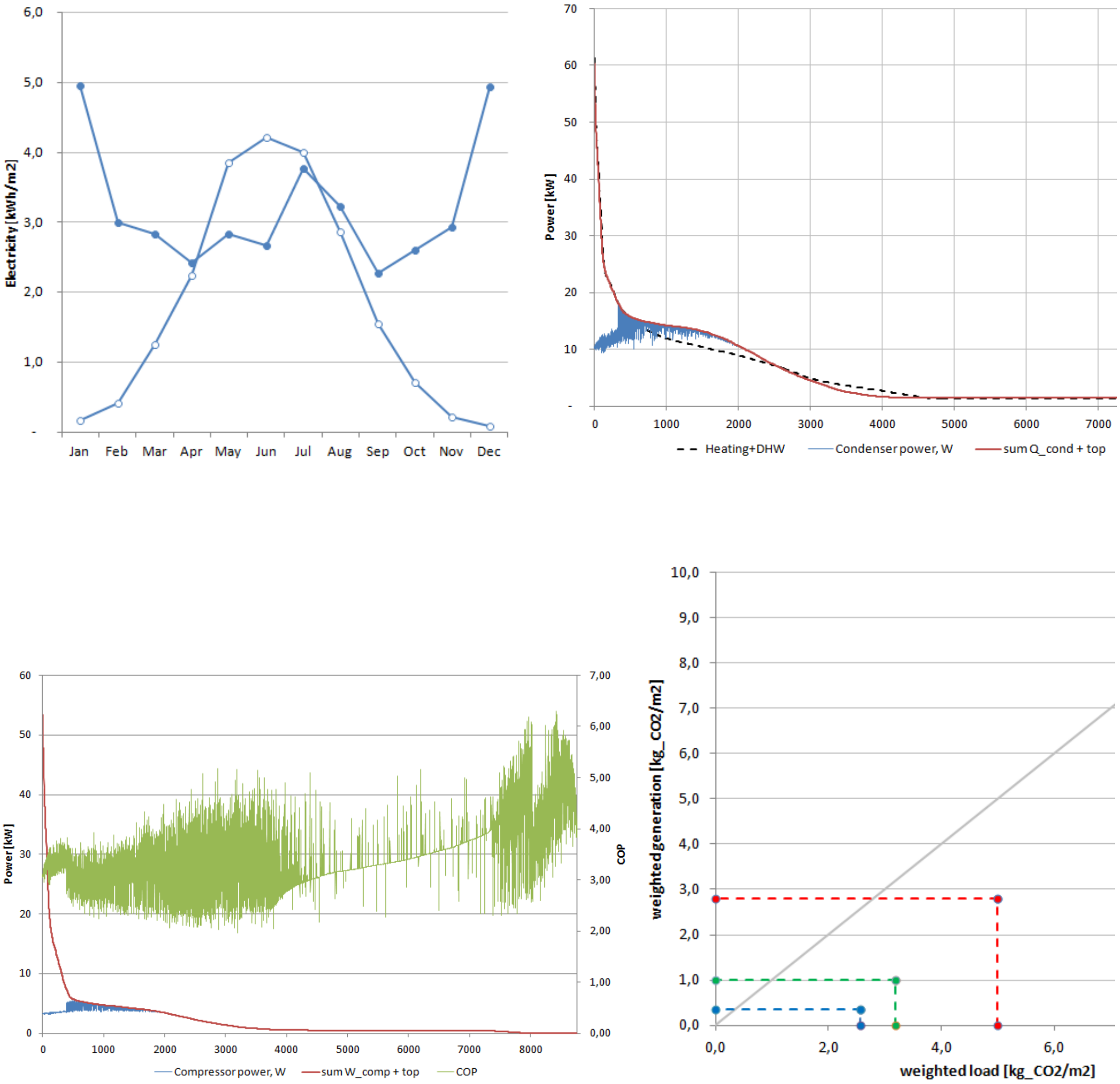


Figure 3.2: Different output graphs

3.1.2 Heat pump parameters optimization

As mentioned, when the base heating system is a heat pump, the first step in the methodology is to adjust its performance according to the manufacturer data. Heat pump manufacturers normally provide different curves that describe how COP, heating capacity and compressor power change with source temperatures. Defining rating conditions in IDA-ICE does not necessarily mean that the heat pump performance is going to vary in the same way as the curves indicated. IDA-ICE parameters should be therefore calibrated to achieve a similar performance. This can be manipulated in the software by setting four calibration parameters (B, C, E and F) which describe the compressor operation. So the excel files used for both ASHP and GSHP optimization give new updated values that will lead to a closer approximation like the one in figure 3.3.

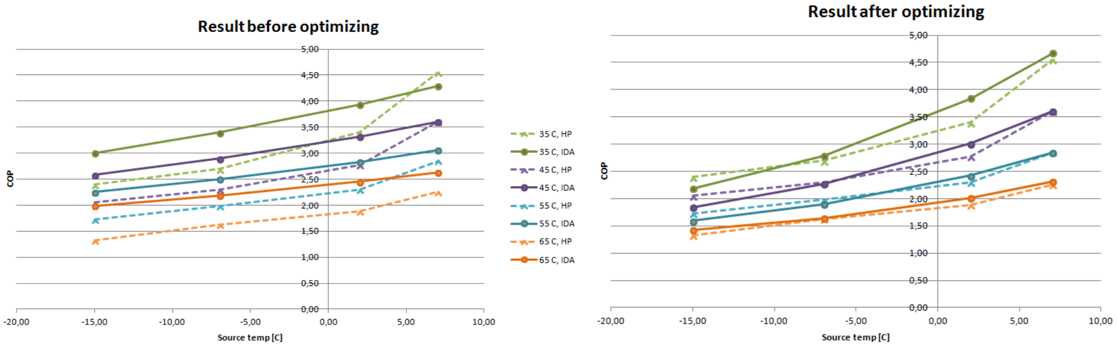
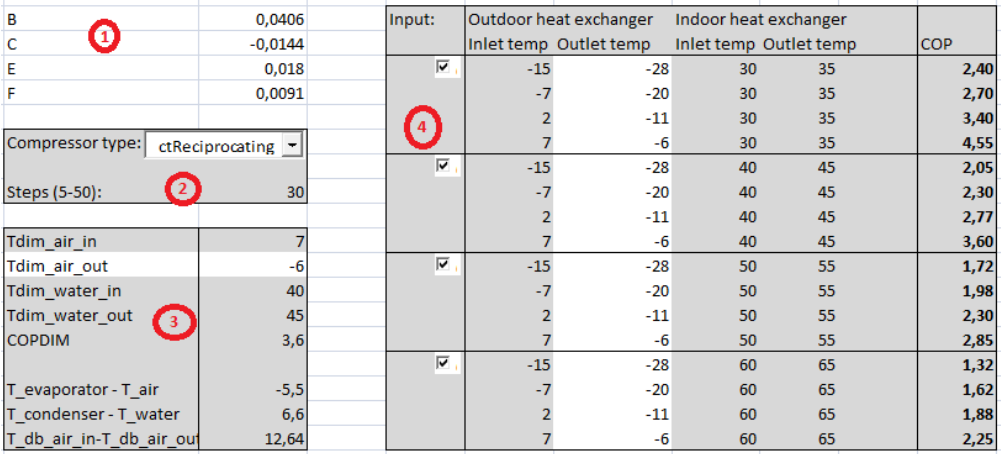


Figure 3.3: Results after and before the optimization

An optimization program has been also developed in Visual Basic for Application (VBA) to calculate the calibration parameters. Figure 3.4 shows the necessary input data for calculations, which will be different for each type of heat pump. Before the optimization, the HP model of IDA-ICE uses four default compressor parameters (1) that should be inserted to make the comparison. The program uses the same algorithm as IDA-ICE to calculate from source temperature and hot water temperature different COPs. Then, after modifying calibration parameters (B, C, D and F), it compares manufacturer's data with COP values calculated by the algorithm. The first step to use this file is to extract real performance data from COP curves given by the manufacturer to complete the performance input table (4). Depending on whether curves for different outlet temperatures are available or not, it is possible to remove the marker in the left column. Rating conditions (3) to define the HP model of IDA-ICE are directly taken from the performance table (4). These numbers are dimensional conditions and define the type of HP simulated in IDA-ICE. In the input sheet is also possible to choose the compressor type (2) from a list of compressors available in IDA-ICE. The election of a new compressor will automatically change default calibration parameters (1). In addition, the user can decide how many B, C, D and F combinations will be tested during calculations defining the amount of steps. For example choosing 30 steps means 30^4 different combinations of parameters and so on.



B	0,0406
C	-0,0144
E	0,018
F	0,0091
Compressor type:	ctReciprocating
Steps (5-50):	30
Tdim_air_in	7
Tdim_air_out	-6
Tdim_water_in	40
Tdim_water_out	45
COPDIM	3,6
T_evaporator - T_air	-5,5
T_condenser - T_water	6,6
T_db_air_in-T_db_air_out	12,64

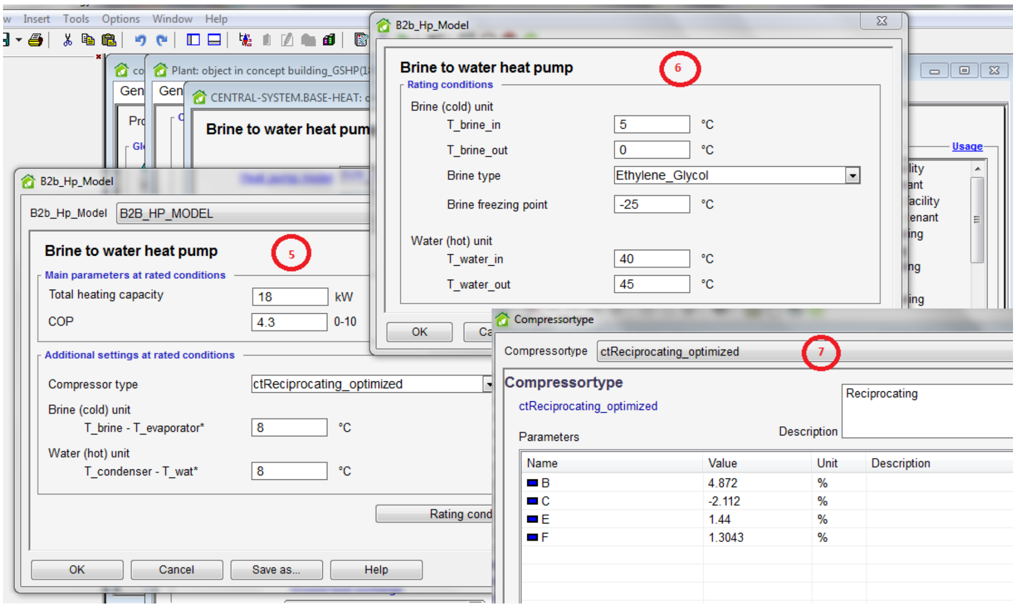
Input:	Outdoor heat exchanger Inlet temp	 Outlet temp	Indoor heat exchanger Inlet temp	 Outlet temp	COP
☑	-15	-28	30	35	**2,40**
	-7	-20	30	35	**2,70**
	2	-11	30	35	**3,40**
	7	-6	30	35	**4,55**
☑	-15	-28	40	45	**2,05**
	-7	-20	40	45	**2,30**
	2	-11	40	45	**2,77**
	7	-6	40	45	**3,60**
☑	-15	-28	50	55	**1,72**
	-7	-20	50	55	**1,98**
	2	-11	50	55	**2,30**
	7	-6	50	55	**2,85**
☑	-15	-28	60	65	**1,32**
	-7	-20	60	65	**1,62**
	2	-11	60	65	**1,88**
	7	-6	60	65	**2,25**

Figure 3.4: Input data for the ASHP optimization excel file

After the optimization, HP rating conditions (6) and new optimized calibration parameters (7) should be introduced in IDA-ICE, as illustrated in figure 3.5. Apart from the total heating capacity and COP for rated conditions (5), also two temperature differences ([T_source - T_evaporator] and [T_condenser – T_water]) have to be written. Both ΔT together with source and hot water temperatures, define the condenser and evaporator temperatures by the following formulas:

$$T_{cond} = \frac{T_{hw\_in} - T_{hw\_out} * exp(\frac{T_{hw_{out}} - T_{hw_{in}}}{T_{cond} - T_{water}})}{1 - \exp\left(\frac{T_{hw_{out}} - T_{hw_{in}}}{T_{cond} - T_{water}}\right)} \qquad \text{(Equation 3.1)}$$

$$T_{evap} = \frac{T_{hw\_in} - T_{hw\_out} * exp(\frac{T_{hw_{out}} - T_{hw_{in}}}{T_{evap} - T_{source}})}{1 - \exp\left(\frac{T_{hw_{out}} - T_{hw_{in}}}{T_{evap} - T_{source}}\right)} \qquad \text{(Equation 3.2)}$$



B2b_Hp_Model: B2B_HP_MODEL

Brine to water heat pump

Main parameters at rated conditions

Total heating capacity: 18 kW

COP: 4.3 (0-10)

Additional settings at rated conditions

Compressor type: ctReciprocating_optimized

Brine (cold) unit

T_brine - T_evaporator*: 8 °C

Water (hot) unit

T_condenser - T_wat*: 8 °C

Brine to water heat pump

Rating conditions

Brine (cold) unit

T_brine_in: 5 °C

T_brine_out: 0 °C

Brine type: Ethylene_Glycol

Brine freezing point: -25 °C

Water (hot) unit

T_water_in: 40 °C

T_water_out: 45 °C

Compressortype: ctReciprocating_optimized

Compressortype

ctReciprocating_optimized

Description: Reciprocating

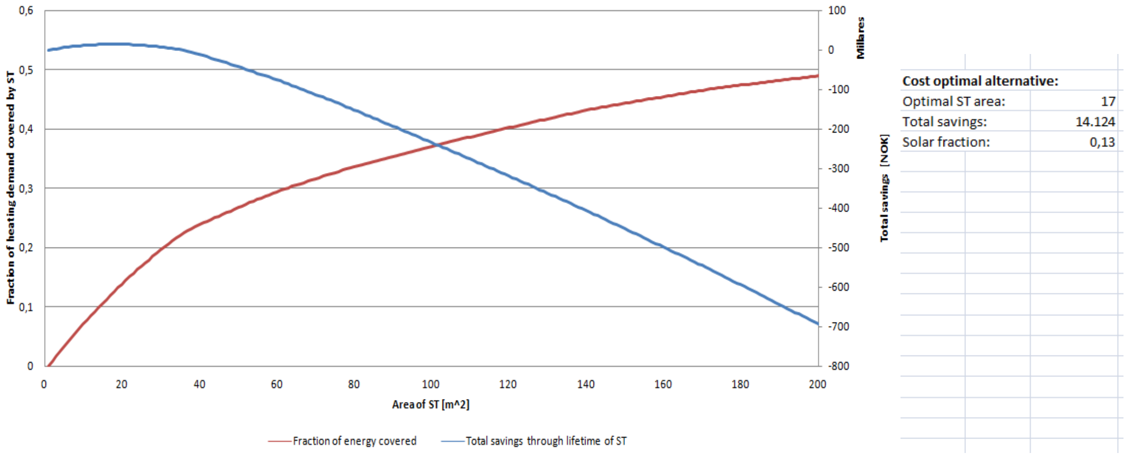
Parameters

Name	Value	Unit	Description
B	4.872	%	
C	-2.112	%	
E	1.44	%	
F	1.3043	%	

Figure 3.5: IDA-ICE input data for a GSHP

3.1.3 ST optimization

Solar thermal collectors are normally installed together with other base load systems to help covering the heating demand of the building. Dimensioning of the solar thermal system must go hand in hand with a previous economical study. It is important to note that the installed system should be able to recover the invested money throughout its lifetime. The theory says that the investment costs increase proportionally with a bigger solar thermal area, while the curve of the heating load fraction covered by the solar thermal decreases in steepness. This means that the area of ST and the power supplied to the building does not increase in the same way. It can be appreciated by analyzing the figure 3.6, where the red line stands for total energy fraction covered by solar thermal and the blue line for total savings through ST lifetime. Therefore, there is a point where energy savings provided by the system during its lifetime are no longer compensating the money invested for the installation. A new tool has been developed in Excel to calculate the area of ST that will provide maximum energy savings to the system.



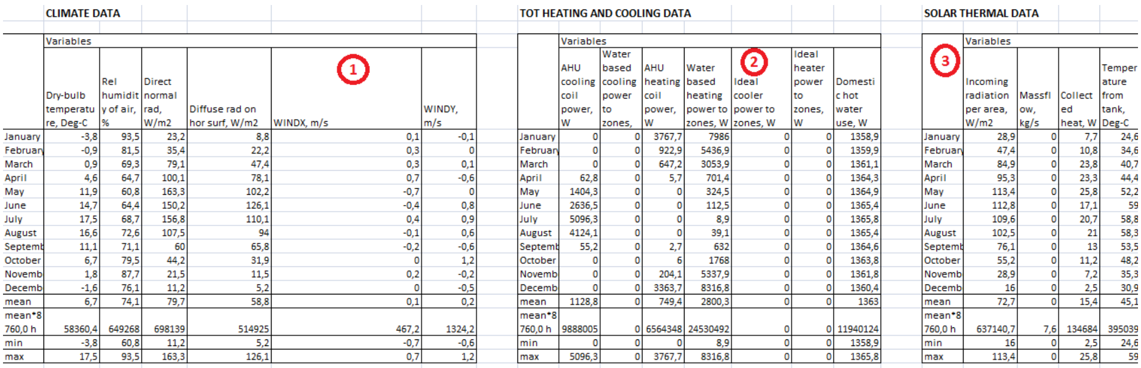
Cost optimal alternative:

Optimal ST area:	17
Total savings:	14.124
Solar fraction:	0,13

Figure 3.6: Results from ST optimizing tool

The Excel file to calculate the optimum solar thermal area is based on the F-chart method. This method provides a means of calculating the heating load fraction that will be covered by a given solar thermal system. The F-chart is essentially a correlation of the results of hundreds of simulations of solar heating systems. The resulting correlations give F, the fraction of the monthly heating load. This value is given as a function of two dimensionless parameters involving collector losses and absorbed solar radiation to heating loads. Hence, monthly average values are needed as an input in the calculation file.

The performance of all solar energy systems depends on the weather factors (ambient air, solar radiation), solar system parameters (collector type, storage capacity) and load characteristics (space and domestic hot water heating, temperature level) [33]. So the file uses an input of three different tables of monthly values collecting all these parameters. Monthly values can be easily copy and paste from output tables of IDA-ICE. The climate table (1) can be obtained directly by opening the climate data and pressing the button "view data". Both the table of total heating and cooling data (2) as well as the one with solar thermal data (3) require running an annual simulation and copying them from the results tab. To reduce the simulation time two different simulations can be performed, one defining the building with the base load heating system and another only with one square meter of solar thermal collector. This is because the incoming radiation data collected in the solar thermal table is expressed per square meter of collector area. It should be highlighted that solar radiation depends on the system´s position, so different tilt angles and orientations will give different data.



CLIMATE DATA

	Variables					
	Dry-bulb temperature, Deg-C	Rel humidity of air, %	Direct normal rad, W/m2	Diffuse rad on hor surf, W/m2	① WINDX, m/s	WINDY, m/s
January	-3,8	93,5	23,2	8,8	0,1	-0,1
February	-0,9	81,5	35,4	22,2	0,3	0
March	0,9	69,3	79,1	47,4	0,3	0,1
April	4,6	64,7	100,1	78,1	0,7	-0,6
May	11,9	60,8	163,3	102,2	-0,7	0
June	14,7	64,4	150,2	126,1	-0,4	0,8
July	17,5	68,7	156,8	110,1	0,4	0,9
August	16,6	72,6	107,5	94	-0,1	0,6
Septemb	11,1	71,1	60	65,8	-0,2	-0,6
October	6,7	79,5	44,2	31,9	0	1,2
Novemb	1,8	87,7	21,5	11,5	0,2	-0,2
Decemb	-1,6	76,1	11,2	5,2	0	-0,5
mean	6,7	74,1	79,7	58,8	0,1	0,2
mean*8760,0 h	58360,4	649268	698139	514925	467,2	1324,2
min	-3,8	60,8	11,2	5,2	-0,7	-0,6
max	17,5	93,5	163,3	126,1	0,7	1,2

TOT HEATING AND COOLING DATA

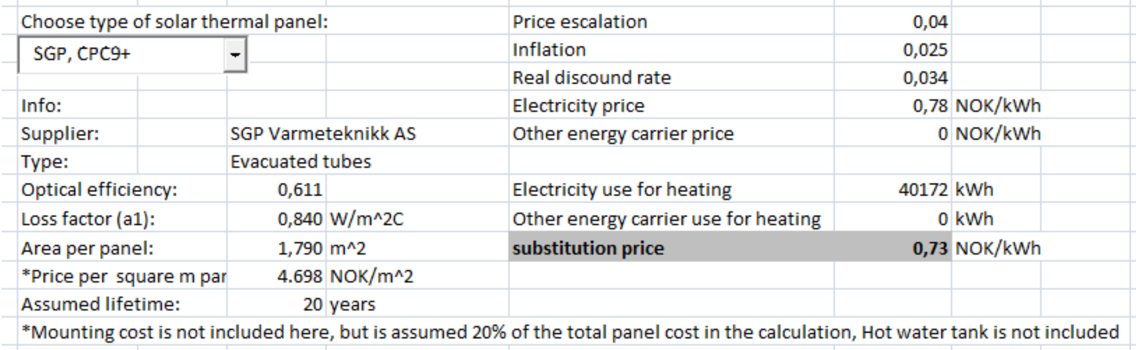
	Variables						
	AHU cooling coil power, W	Water based cooling power to zones,	AHU heating coil power, W	Water based heating power to zones, W	② Ideal cooler power to zones, W	Ideal heater power to zones, W	Domestic hot water use, W
January	0	0	3767,7	7986	0	0	1358,9
February	0	0	922,9	5436,9	0	0	1359,9
March	0	0	647,2	3053,9	0	0	1361,1
April	62,8	0	5,7	701,4	0	0	1364,3
May	1404,3	0	0	324,5	0	0	1364,9
June	2636,5	0	0	112,5	0	0	1365,4
July	5096,3	0	0	8,9	0	0	1365,8
August	4124,1	0	0	39,1	0	0	1365,4
Septemb	55,2	0	2,7	632	0	0	1364,6
October	0	0	6	1768	0	0	1363,8
Novemb	0	0	204,1	5337,9	0	0	1361,8
Decemb	0	0	3363,7	8316,8	0	0	1360,4
mean	1128,8	0	749,4	2800,3	0	0	1363
mean*8760,0 h	9888005	0	6564348	24530492	0	0	11940124
min	0	0	0	8,9	0	0	1358,9
max	5096,3	0	3767,7	8316,8	0	0	1365,8

SOLAR THERMAL DATA

③	Variables			
	Incoming radiation per area, W/m2	Massflow, kg/s	Collected heat, W	Temperature from tank, Deg-C
January	28,9	0	7,7	24,6
February	47,4	0	10,8	34,6
March	84,9	0	23,8	40,7
April	95,3	0	23,3	44,4
May	113,4	0	25,8	52,2
June	112,8	0	17,1	59
July	109,6	0	20,7	58,8
August	102,5	0	21	58,3
Septemb	76,1	0	13	53,5
October	55,2	0	11,2	48,2
Novemb	28,9	0	7,2	35,3
Decemb	16	0	2,5	30,9
mean	72,7	0	15,4	45,1
mean*8760,0 h	637140,7	7,6	134684	395039
min	16	0	2,5	24,6
max	113,4	0	25,8	59

Figure 3.7: Input tables for the ST optimizing tool

In addition, the user should choose which type of thermal panel is being used with its specific characteristics and also some economical parameters, as it has been done in figure 3.8. These parameters must be written manually. Then, the file will calculate the money gained or lost by covering a part of the load with solar thermal rather than using another energy supply system, namely substitution price.



Choose type of solar thermal panel:			Price escalation	0,04	
SGP, CPC9+			Inflation	0,025	
			Real discount rate	0,034	
Info:			Electricity price	0,78	NOK/kWh
Supplier:	SGP Varmeteknikk AS		Other energy carrier price	0	NOK/kWh
Type:	Evacuated tubes				
Optical efficiency:	0,611		Electricity use for heating	40172	kWh
Loss factor (a1):	0,840	W/m^2C	Other energy carrier use for heating	0	kWh
Area per panel:	1,790	m^2	**substitution price**	**0,73**	NOK/kWh
*Price per square m par	4.698	NOK/m^2			
Assumed lifetime:	20	years			

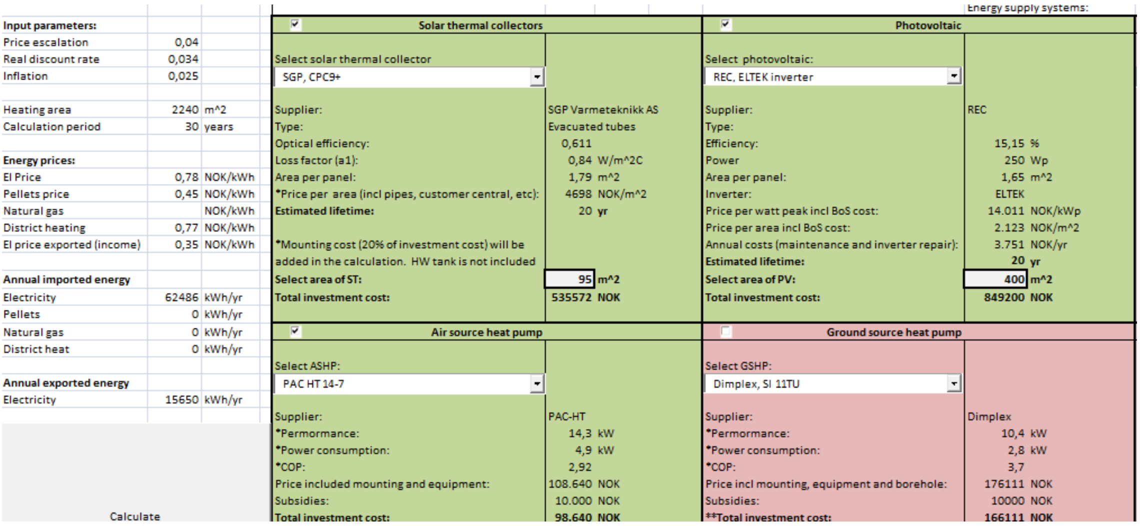
*Mounting cost is not included here, but is assumed 20% of the total panel cost in the calculation, Hot water tank is not included

Figure 3.8: Input for the ST optimizing tool

Like the previous figure 3.6 shows, the file will give as a result the optimal ST area for the selected base load heating system, the solar fraction and the corresponding savings for that solar thermal area.

3.1.4 Cost analysis

Based on the cost-optimal methodology theory, previously explained in chapter 2.4, this file of the early design phase methodology is going to be used to perform global cost calculations. The user can select different combinations of energy supply systems by marking the corresponding box, which will be colored in green. Actually the input sheet has a list of available technologies in Norway, collected during the project [55], and sets automatically technical and economic parameters for each system. Nevertheless, input parameters can also be changed manually in case of using another technology that is not included in the file. Energy and economic parameters should also be inserted as input data, like price escalation, real discount rate, inflation, energy prices, annual imported energy separated in energy carriers and annual exported energy. Imported and exported energy has to be taken from IDA-ICE results while economic parameters depend on the country where the study is performed.



Input parameters:		
Price escalation	0,04	
Real discount rate	0,034	
Inflation	0,025	
Heating area	2240	m^2
Calculation period	30	years
Energy prices:		
El Price	0,78	NOK/kWh
Pellets price	0,45	NOK/kWh
Natural gas		NOK/kWh
District heating	0,77	NOK/kWh
El price exported (income)	0,35	NOK/kWh
Annual imported energy		
Electricity	62486	kWh/yr
Pellets	0	kWh/yr
Natural gas	0	kWh/yr
District heat	0	kWh/yr
Annual exported energy		
Electricity	15650	kWh/yr

Calculate

Energy supply systems:

☑ Solar thermal collectors		
Select solar thermal collector		
SGP, CPC9+		
Supplier:	SGP Varmeteknikk AS	
Type:	Evacuated tubes	
Optical efficiency:	0,611	
Loss factor (a1):	0,84	W/m^2C
Area per panel:	1,79	m^2
*Price per area (incl pipes, customer central, etc):	4698	NOK/m^2
Estimated lifetime:	20	**yr**
*Mounting cost (20% of investment cost) will be added in the calculation. HW tank is not included		
Select area of ST:	95	**m^2**
Total investment cost:	535572	NOK

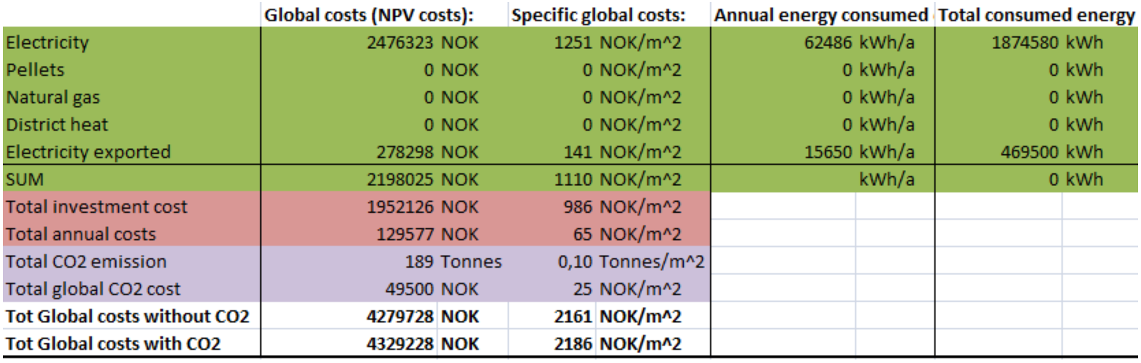
☑ Photovoltaic		
Select photovoltaic:		
REC, ELTEK inverter		
Supplier:	REC	
Type:		
Efficiency:	15,15	%
Power	250	Wp
Area per panel:	1,65	m^2
Inverter:	ELTEK	
Price per watt peak incl BoS cost:	14.011	NOK/kWp
Price per area incl BoS cost:	2.123	NOK/m^2
Annual costs (maintenance and inverter repair):	3.751	NOK/yr
Estimated lifetime:	20	**yr**
Select area of PV:	400	**m^2**
Total investment cost:	849200	NOK

☑ Air source heat pump		
Select ASHP:		
PAC HT 14-7		
Supplier:	PAC-HT	
*Permormance:	14,3	kW
*Power consumption:	4,9	kW
*COP:	2,92	
Price included mounting and equipment:	108.640	NOK
Subsidies:	10.000	NOK
Total investment cost:	98.640	NOK

☐ Ground source heat pump		
Select GSHP:		
Dimplex, SI 11TU		
Supplier:	Dimplex	
*Permormance:	10,4	kW
*Power consumption:	2,8	kW
*COP:	3,7	
Price incl mounting, equipment and borehole:	176111	NOK
Subsidies:	10000	NOK
****Total investment cost:**	166111	NOK

Figure 3.9: Input sheet for the cost analysis excel file

After setting all the parameters, calculation bottom is pressed and the program will calculate total global costs for the chosen calculation period. It can be seen in figure 3.10 that the results sheet gives total investment and annual cost as well as the sum of energy costs. It also calculates the CO_2 costs related to the energy used in the building for a macroeconomic perspective.



	Global costs (NPV costs):		Specific global costs:		Annual energy consumed		Total consumed energy	
Electricity	2476323	NOK	1251	NOK/m^2	62486	kWh/a	1874580	kWh
Pellets	0	NOK	0	NOK/m^2	0	kWh/a	0	kWh
Natural gas	0	NOK	0	NOK/m^2	0	kWh/a	0	kWh
District heat	0	NOK	0	NOK/m^2	0	kWh/a	0	kWh
Electricity exported	278298	NOK	141	NOK/m^2	15650	kWh/a	469500	kWh
SUM	2198025	NOK	1110	NOK/m^2		kWh/a	0	kWh
Total investment cost	1952126	NOK	986	NOK/m^2				
Total annual costs	129577	NOK	65	NOK/m^2				
Total CO2 emission	189	Tonnes	0,10	Tonnes/m^2				
Total global CO2 cost	49500	NOK	25	NOK/m^2				
Tot Global costs without CO2	**4279728**	**NOK**	**2161**	**NOK/m^2**				
Tot Global costs with CO2	**4329228**	**NOK**	**2186**	**NOK/m^2**				

Figure 3.10: Results for the cost analysis excel file

3.1.5 Comparison of energy systems and final selection of cost-optimal methodology

Different energy supply alternatives have to be presented in terms of global costs and consumption of primary energy or CO_2 emissions, like in the graph of figure 3.25. Obviously the cost-optimal system does not necessarily have to be within the desired energy performance level. For that reason, the final selection has to be in accordance with both values. Actually, there are different energy performance requirements that can be fulfilled in a cost-optimal analysis, which will set a limit for the weighted energy consumption. When meeting these requirements, the optimal alternative will be the one associated with the lowest global costs.

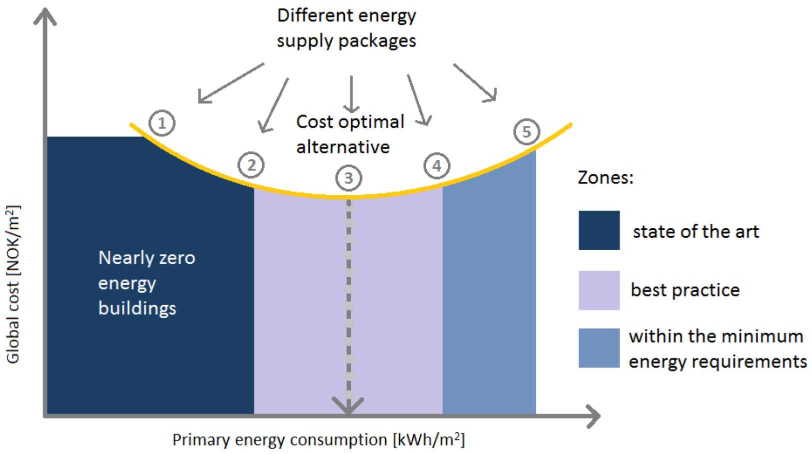


Figure 3.11: Deciding the cost optimal system [14]

Following with the early design phase methodology, cost analysis results of different systems have to be collected in a common Excel file. This will present the results in a graph which divides global costs in three categories: maintenance costs, energy costs and investment costs. When performing a macroeconomic analysis costs associated to CO_2 emissions will be also included in each column.

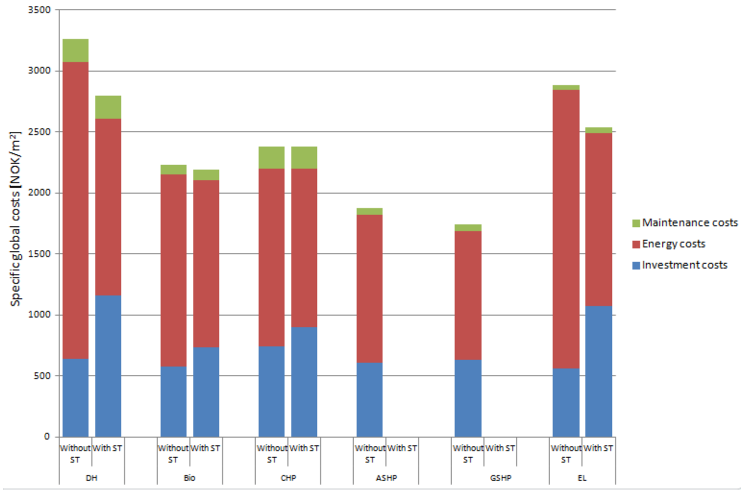


Figure 3.12: Cost analysis results for the early design phase methodology

As mentioned before, the optimal system will be selected using a graph like the one below. First of all, it should be checked which alternatives meet the energy requirements and then, the user simply has to choose the energy system with lower global costs. If two or more systems have similar global costs, the one with the least weighted energy consumption should be the preferred alternative.

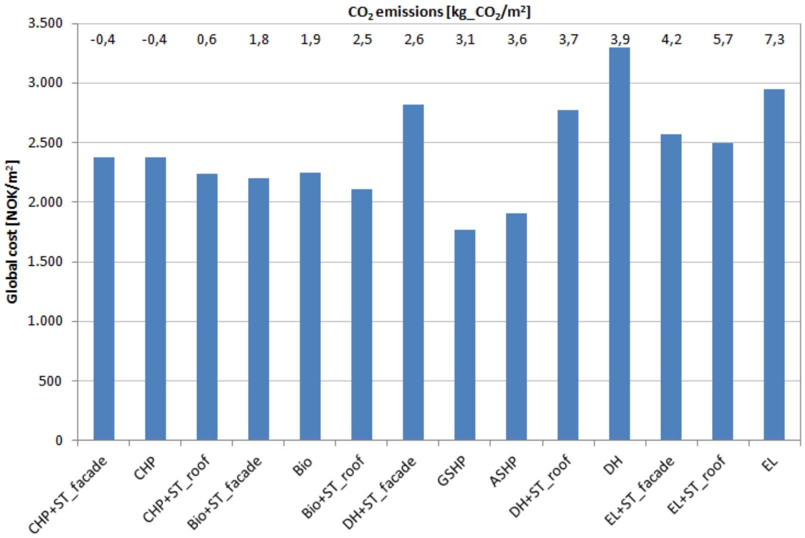


Figure 3.13: Final results given in a cost-emissions graph

3.2 Building model

The building used for the study is a concept office building previously defined in [34] and also used during the project [35]. It is a four storey high building with an unheated basement, hence not included in the heat floor area (BRA). With the aim that it can be used in any Norwegian zero emission building analysis, it has been defined with the typical parameters that an office building of this category should have. The dimension of the building footprint is 17x30 m^2 with the longest façades facing north and south. Of the total area per floor, 495 m2 is heated floor while 15 m^2 is unheated stairs, giving a total area of 1980 m^2 BRA. The office building has been directly modelled in IDA-ICE, determining those parameters that are necessary for a correct performance and suppressing those which are not.

As the figure 3.14 shows, even if the real concept building [34] has four floors, the model used only contains three. This is a simplification made after assuming that middle floors are identical, thus only one is modelled and later the simulations results for that floor are multiplied by two. When dimensioning each zone, only the heated part will be considered. Besides, every floor is analyzed as one big zone, so there is not any room division inside. There is a separation between each floor, normally bigger than 0.6 m because then IDA-ICE automatically considers that surfaces have no adjacent face. The heat transfer between zones is therefore ignored, as wanted. Finally, all windows in each zone façade are reduced to large windows with the same area. All of them are acceptable simplifications considering that only the energy consumption is evaluated and they do not have a significant influence in the final results. Following all these steps, it is possible to reduce considerably the simulation time, which can be very long when evaluating the energy performance of the building over the whole year.

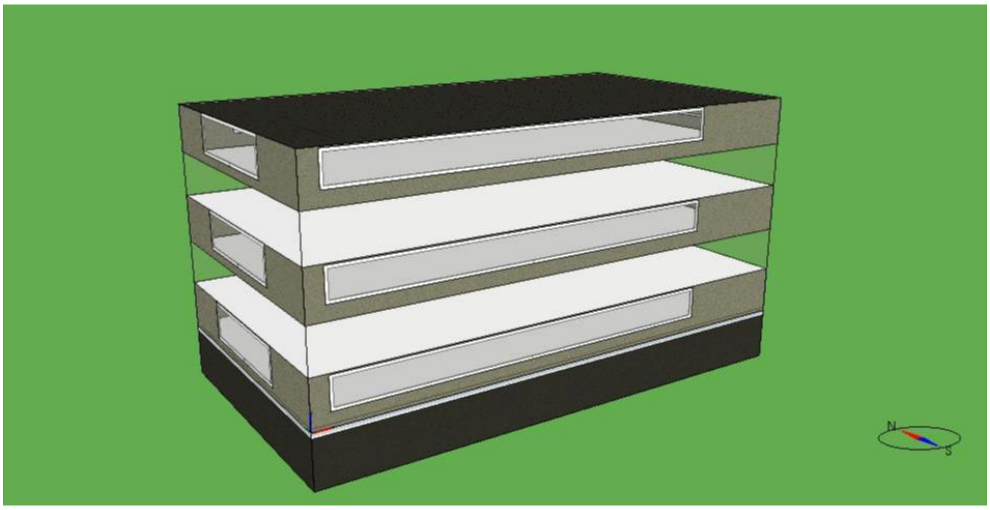


Figure 3.14: Screenshot from IDA-ICE, 3D representation of the model.

3.2.1 Building envelope

A zero emission building is characterized by a well insulated envelope with low heat transmission to the environment. To ensure a reliable simulation of the building's thermal behaviour, it is necessary to define correctly transmission coefficients or U-values, which define the mentioned heat transfer through the construction. IDA-ICE gives the possibility of selecting elements for walls, roof and floors from an extensive database. Elements composing the envelope have been decided following the report [34]. The most important part when trying to reach a low transmittance is to select enough insulation thickness and conductivity value for each wall. In the floor against the basement a construction that gives a U-value of 0.14 W/m^2k has been decided, however, due to the heat loss factor of the unheated basement the effective value is approximately 0.11 W/m^2k. The windows have a typical value for low energy buildings of 0.75 W/m^2k, even if the glass has a higher transmittance the average between window and frame gives that value. In the table below the most important specifications for the simulations are presented, they are usually similar values to the passive house requirements of NS 3701.

Parameters	Value	
U-value external walls	0,12	W/m^2k
U-value floor against the basement	0,11	W/m^2k
U-value roof	0,09	W/m^2k
U-value windows	0,75	W/m^2k
Leakage number	0,5	h^{-1}
Thermal bridges	0,03	W/m^2k
Air tightness	≤ 0,3	

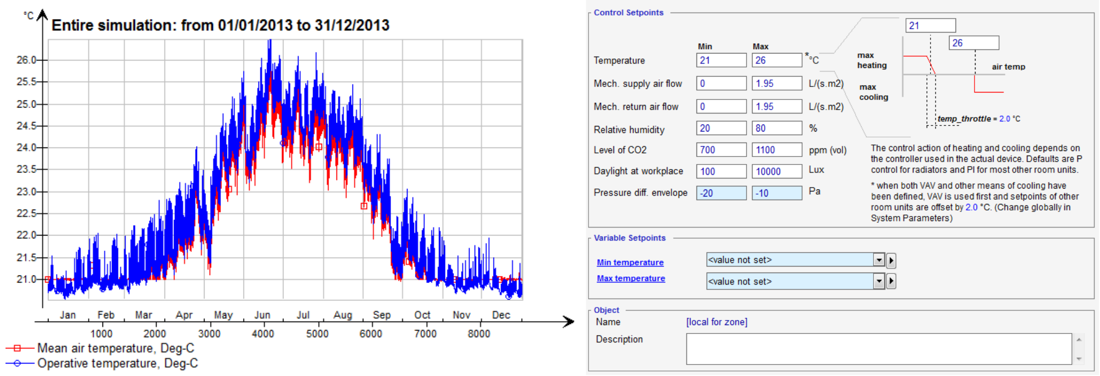
Table 3.1: Main parameters for the concept building envelope

3.2.2 Technical installations

The energy demand reduction of building services for passive houses and zero emission buildings is nowadays an important field of study. Every new technical code establishes renovated specifications for progressively lower energy consumption. The final goal is to reach a very high performance in the HVAC (heating, cooling and air conditioning) system maintaining at the same time indoor conditions. Especially in office buildings, where indoor spaces have to offer an adequate indoor air quality (IAQ) and thermal comfort for the workers, a correct installation design is a very important step. For that reason national requirements and standards should be respected in order to ensure comfort and maximum occupant productivity.

As building technical codes incorporate stricter requirements for tightness of building envelopes, cooling needs are increased. Better insulated buildings together with internal heat gains and solar radiation make that many offices in Northern Europe need cooling of the building during a major part of the year. A fraction of solar radiation received through windows and other openings contributes to heating the building. Furthermore, internal heat gains also tend to raise indoor temperature, which is helpful in winter, however in winter has to be controlled by cooling the indoor space. Internal heat gains means heat emitted from lights, equipment and people inside the building. The study of how to design building's technical installations to achieve a realistic cooling demand in offices has been an important part of this project. All the parameters set in this section heavily influence energy demand, thus a balance should be found to lower the consumption while normative requirements are fulfilled.

The difference between outdoor temperature and indoor temperature is decisive for a building's heat loss. This affects both the heat loss through ventilation and the heat lost through the building envelope [24]. IDA-ICE mainly controls two temperatures in each zone: mean air temperature and operative temperature. The first one measures the air temperature of each zone and it is normally limited within indoor comfort temperatures. To guarantee a satisfactory temperature inside the building, set points should not allow this to be lower than 21ºC in winter and higher than 26ºC in summer. The operative temperature is the one that should be checked during simulations, ensuring that it is within the limits. It is an average between the mean air temperature and the mean radiant temperature (MRT) or temperature felt by a human body, which is a means of expressing the influence of surface (walls, windows, ceiling and floor) temperatures on occupant comfort. When the building envelope is very hot due to solar and heat gains, usually in summer, T_{op} is higher than T_{air} and vice versa. TEK10 states that the operative temperature should not exceed 26ºC more than 50 hours per year, which it should be checked for the summer period.



Control Setpoints

	Min	Max	
Temperature	21	26	*°C
Mech. supply air flow	0	1.95	L/(s.m2)
Mech. return air flow	0	1.95	L/(s.m2)
Relative humidity	20	80	%
Level of CO2	700	1100	ppm (vol)
Daylight at workplace	100	10000	Lux
Pressure diff. envelope	-20	-10	Pa

temp_throttle = 2.0 °C

The control action of heating and cooling depends on the controller used in the actual device. Defaults are P control for radiators and PI for most other room units.

* when both VAV and other means of cooling have been defined, VAV is used first and setpoints of other room units are offset by 2.0 °C. (Change globally in System Parameters)

Variable Setpoints

Min temperature <value not set>
Max temperature <value not set>

Object

Name: [local for zone]
Description:

Figure 3.15: Zone temperatures and set point control parameters

Plant and water distribution system

IDA-ICE offers by default the plant model shown in figure 3.16. Hot and cold storage tanks are responsible to store and deliver water at required temperatures for heating and cooling purposes. Base and peak heating systems provide heated water to the hot tank, which is simultaneously connected with heating room units, DHW distribution system and ventilation system's heating coil. A chiller is the only system available by IDA-ICE to supply cold water to the cold tank. However in reality cold water can be also provided for example with a reversible heat pump working in cooling mode; how to simulate this particular case will be studied later. The cold storage tank works in the same way as the hot tank, so it is connected with the cooling coil and possible cooling room units.

Hot and cold water distribution temperatures strongly influence the final energy consumption of the building. Distribution systems connect plant storage tanks with the AHU system and different room units. Water is distributed through pipes from the hot and cold tank to heating and cooling coils in the ventilation system. In addition, heat is also distributed from the storage tank and carried out to each zone via hydronic radiators. Low energy buildings like ZEBs usually use low temperature heating and high temperature cooling, since both types of distribution are actually regarded as the most efficient. Increasing water temperature for cooling and decreasing temperature for heating imply reducing losses and total energy consumption. The lower limit in a heating system and the higher limit in a cooling system are restricted by the size of terminal units [36].

Since this project is particularly focused in the introduction of cooling for offices, special attention has been given to the cooling water temperature for ventilation. This is the temperature of the water delivered from the cold storage tank to the cooling coil. Supplying water temperature for the coil is restricted from below by the freezing, condensing or comfort temperature. From above, as mentioned before, is restricted by the maximum allowed size of the terminal unit. Smaller temperature difference between water and air results in larger terminal units, i.e. a larger cooling coil.

The main purpose of the air distribution components is to treat the air, cool it in this case. This process requires a minimum pressure drop over the component to work properly. However, this pressure drop should be kept as low as is economically feasible. But if the supply water temperature in the cold distribution system increases, the temperature difference will be higher creating also high pressure drop, what can be a problem for the system. For that reason, commonly used temperatures levels are water supply temperatures to the cooling coil between 6-7ºC and air supply temperatures to the room around 16-18ºC [36]. Zone cooling will also require larger room units with higher distribution temperature. An exception is ceiling panels, where higher supply temperatures are generally needed to avoid condensation. Nevertheless ceiling panels have been discarded by the complexity of design and the final decision of only using ventilated cooling.

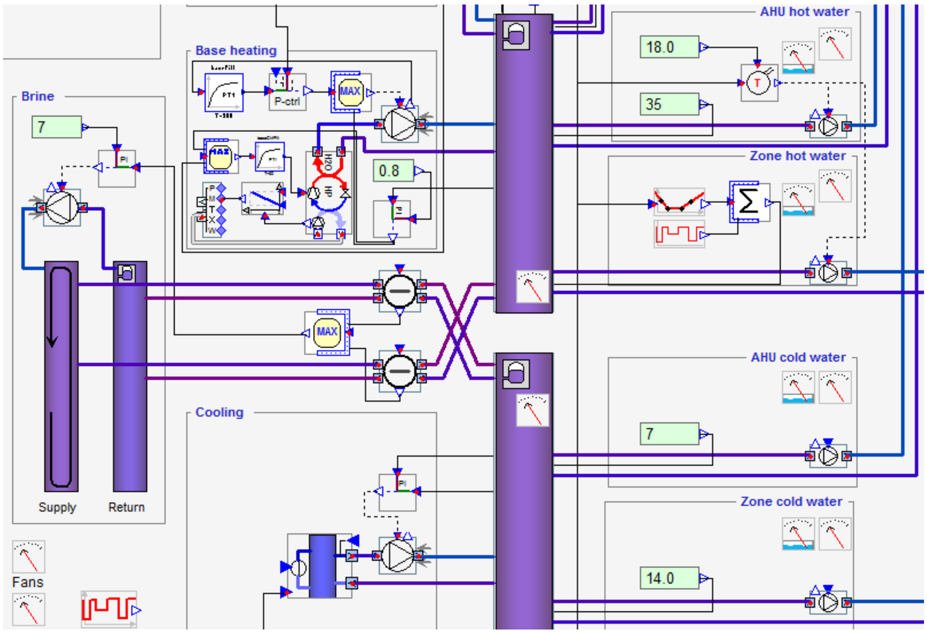


Figure 3.16: Plant model of IDA-ICE

HVAC system

Energy used for heating, ventilation and air conditioning (HVAC) is a major part of the total energy demand of Norwegian buildings. With this in mind, during the project an extended study has been performed to decide the most efficient system for a building of these characteristics. From the beginning a system based on heating/cooling ventilation has been considered as one of the best and most efficient options. Simulations have shown that a ventilation system for cooling during summer days and heating in cold days of winter together with heating room units is a good way to satisfy indoor requirements, while maintaining low energy consumption and power peaks. Therefore the ventilation system is responsible for removing stale air and replenishing with fresh air that heats and cools the building depending on the season.

It should be noted that the final decision for the HVAC system has been limited by the available possibilities in IDA-ICE. Without an advanced version and a deep knowledge of the software it is difficult to study all the possible technical installations for a low energy building. Anyway this project is more focus in the selection of the energy supply system rather than the HVAC system.

Air Handling Unit

An Air Handling Unit (AHU) is a device used to condition and circulate the air as part of the HVAC system. This unit contains all the necessary systems to supply air in the building at desired conditions. As shown in figure 3.17, the model of IDA-ICE is a simple system formed by two ducts for both supply and exhaust air. Each of the pipes has a fan responsible for the air movement with the need of certain electric energy to power them. Their efficiency is given by the specific fan power (SPF) which should be set following existing requirements. New energy efficient buildings also incorporate a heat exchanger inside the AHU. Heat recovery from exhaust air has become an important part because energy recovered reduces the need for new power.

The system operation is simple: outdoor air is circulated through the air supply duct where the heating coil increases the air temperature during the heating season, while the cooling coil decreases it during the cooling season. As explained before, the energy needed for the coils is obtained from the plant. After crossing the corresponding coil, conditioned air will be supplied to the building at desired supply temperature and airflow rate, which can be controlled by schedules. Fresh air will replace old air which will be expelled by the exhaust duct, recovering first certain amount of heat energy with the heat exchanger.

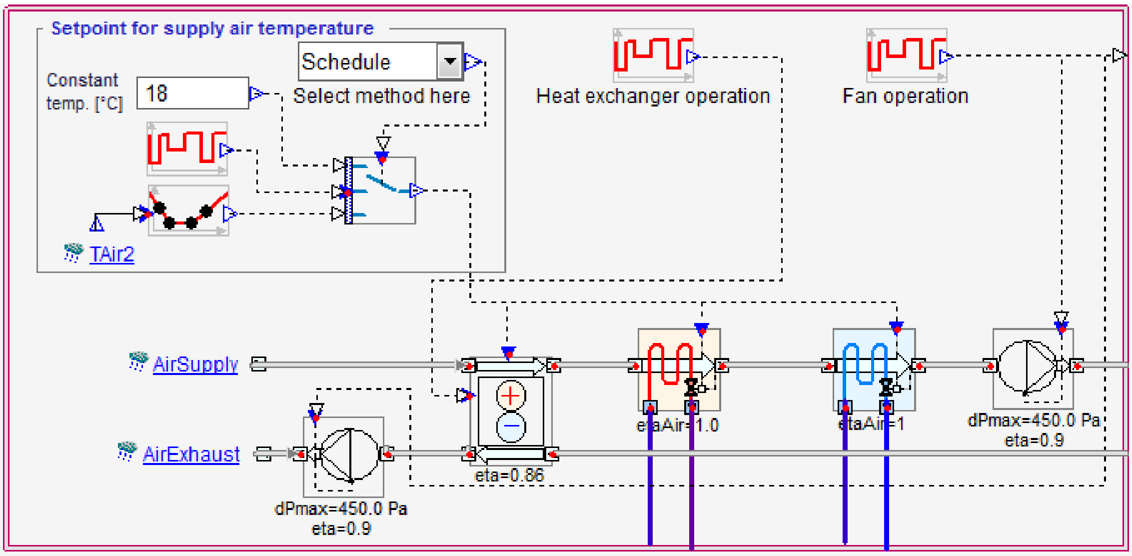
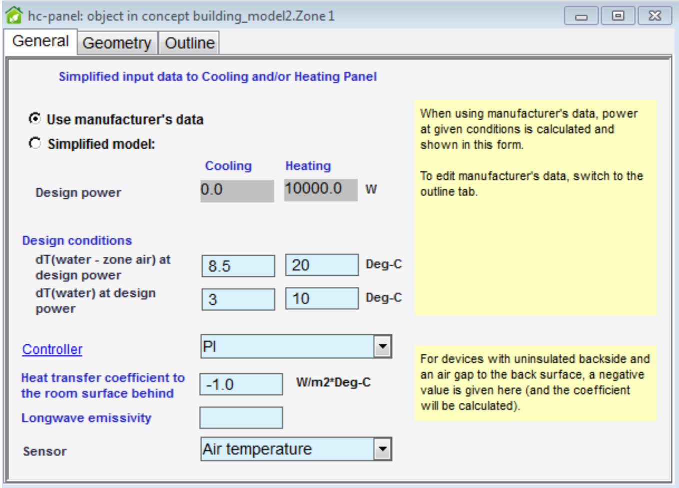


Figure 3.17: AHU system, taken from IDA-ICE

Room units

Space heating is supplied at the same time by ventilation air and heating room units. Heating/Cooling panels have been defined as zone units with enough capacity to cover the zone heating load. This capacity has been decided by installing first an ideal heater, taking results from simulations and sizing the panel with an overestimated value, namely 10000W per zone. In this case, cooling capacity is 0W because it has been assumed that cooling load is small enough that the entire cooling demand can be covered with the ventilation system. Other parameters in figure 3.18 are default values of hc-panel models in IDA-ICE.



Simplified input data to Cooling and/or Heating Panel

● Use manufacturer's data
○ Simplified model:

	Cooling	Heating	
Design power	0.0	10000.0	W
Design conditions			
dT(water - zone air) at design power	8.5	20	Deg-C
dT(water) at design power	3	10	Deg-C

Controller: PI

Heat transfer coefficient to the room surface behind: -1.0 W/m2*Deg-C

Longwave emissivity:

Sensor: Air temperature

When using manufacturer's data, power at given conditions is calculated and shown in this form.

To edit manufacturer's data, switch to the outline tab.

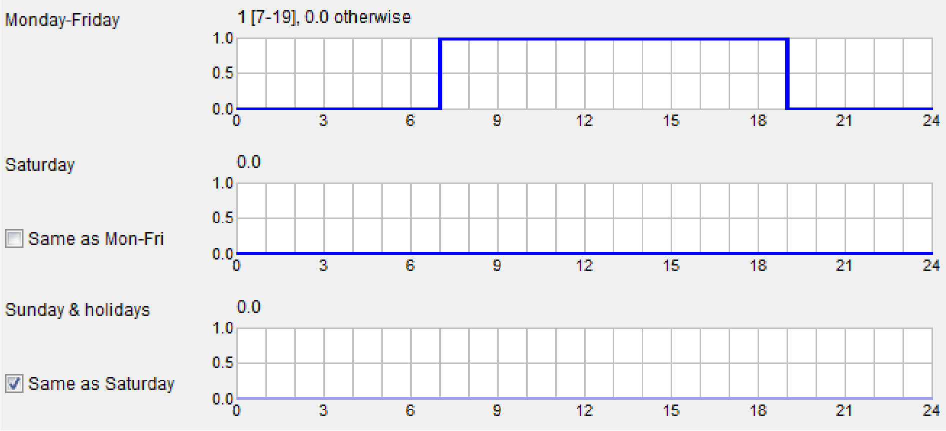
For devices with uninsulated backside and an air gap to the back surface, a negative value is given here (and the coefficient will be calculated).

Figure 3.18: Parameters for hc-panels, taken from IDA-ICE

Ventilation system control

One of the critical points when trying to give a real approach to the model is to decide an appropriate control of the ventilation air. Since this system stands for the greater amount of energy consumption in the building, different cases have been simulated and compared according to required indoor conditions. A Variable-air-volume (VAV) ventilation system varies the air volume that is supplied to meet changing load conditions of the space. A real VAV system works by increasing and decreasing the supplied airflow in response to changes of different indoor parameters, such as occupancy, CO_2 levels, humidity and indoor temperature. In addition, it may also vary the supply temperature from the standard value of 18 ºC down to lower values during hot days, always limiting the temperature to avoid cold drafts which is cause of discomfort for workers. However, the AHU model that supplies air temperature to the building does not allow varying this temperature according to return temperature from the room. The AHU control system that can be defined in IDA-ICE makes a more coarse approach having the outdoor temperature as variation reference.

Besides, the occupancy schedule used for energy simulations is also a limitation for the VAV system. The normative approach in both NS3701 and NS3031 used in this project, assumes a constant occupancy between 7 and 19 during workdays, as it can be seen in figure 3.19. NS3031 also sets standard airflow values for calculations of net energy in office buildings, giving an airflow rate of $6m^3/m^2h$ in hours of operation (workdays) and $1m^3/m^2h$ outside hours of operation (night/weekends). This means that normally in energy simulations, where constant occupancy schedules are used, there is no need to used VAV system based on temperature or CO_2 level control. Summarizing, to control the ventilation air supplied to the zones two schedules should be set, one for air supply temperature and another for airflow rates. During the design process both parameters have been defined selecting values near standards and searching for the lower consumption alternative.



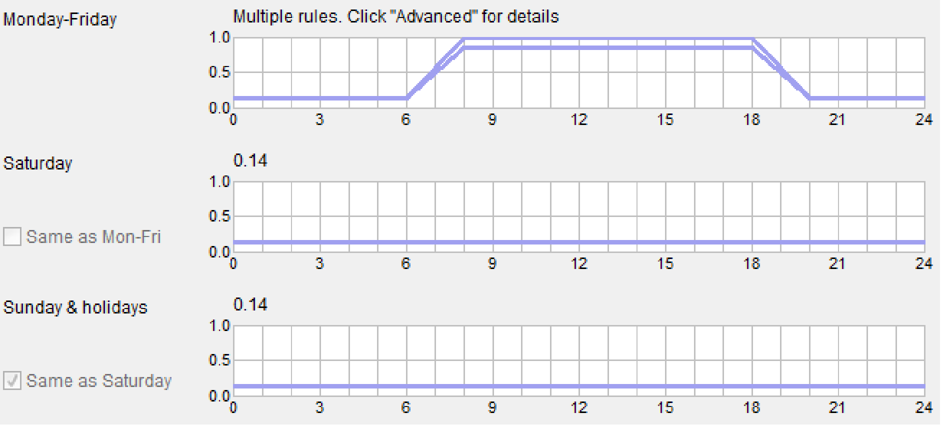
Monday-Friday
1 [7-19], 0.0 otherwise

Saturday
0.0
☐ Same as Mon-Fri

Sunday & holidays
0.0
☑ Same as Saturday

Figure 3.19: Occupancy schedule, taken from IDA-ICE

A trial and error process simulating different combination of parameters has concluded with the most suitable system. The first decision taken has been how to relate the occupancy schedule (figure 3.19) and the airflow schedule (figure 3.20) to avoid wasting energy. In a normal office the system should start conditioning the rooms before workers arrive. As the occupancy schedule is assuming that the office is instantaneously full of workers at 7 and empty at 19, the airflow increases from 6 to 8 with a ramp shaped line and decreases in the same way from 18 to 20. In this way heating and cooling do not show high peaks, which may be formed due to high airflows when there is no occupancy. Respecting standards the system is supplying $1m^3/m^2h$ in nights/weekends and $6m^3/m^2h$ in workdays during the heating season. On the other hand in the cooling season workdays the airflow should be raised to $7m^3/m^2h$. This is basically because heating is supplied also by room units unlike cooling which is completely covered by ventilation, so there is a need for a higher volume in the cooling season. A change of units should be performed before because IDA-ICE requires defining the mechanical airflow in $L/s.m^2$.



Monday-Friday

Multiple rules. Click "Advanced" for details

Saturday

0.14

☐ Same as Mon-Fri

Sunday & holidays

0.14

☑ Same as Saturday

Figure 3.20: Airflow schedule, taken from IDA-ICE

Regarding the mechanical air supply temperature, the standard value of 18ºC throughout the year has been finally set. Initially using 16ºC in summer was considered, however this value results in really high cooling peaks in the warmest days of summer. Simulations also showed that a supply of 18ºC degrees with a minimum airflow during weekends was a cause of overheating in summer. A good way to solve this problem is to combine ventilation with an automatic opening of windows. Windows are controlled with on/off control at 24ºC and limited to 5% during occupation, i.e. when indoor temperature reaches 24 ºC every window of the zone is opened a 5% until it decreases again. It should be highlighted that windows cannot be completely opened. According to building technical standards, inflow though windows should be lower than 4000 l/s which is an acceptable value when all windows are opened. Results show that it seldom goes up to higher values.

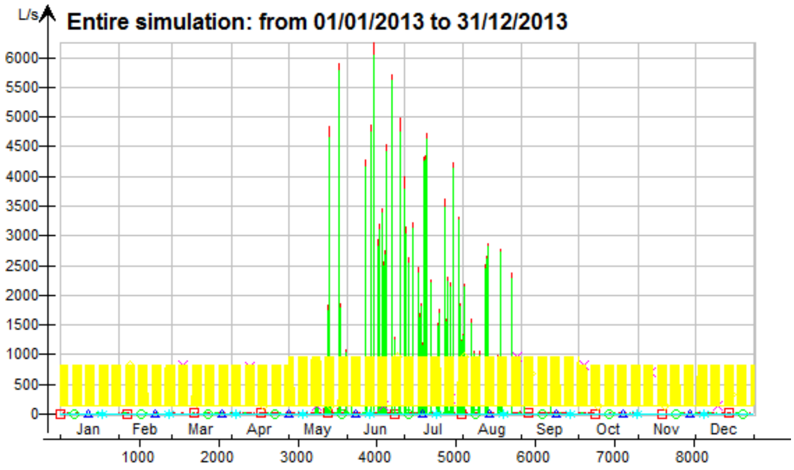


Figure 3.21: Airflow in a zone with on/off window opening, taken from IDA-ICE

Input parameters

Parameter	**Value**
Heat recovery ventilation	86%
Specific fan power (SPF)	0,5 kW/(m^3/s) each fan
Fan efficiency	90%
Air flow temperature	18 ºC
Air flow rate in hours of operation, heating season	6,0 m^3/m^2h
Air flow rate in hours of operation, cooling season	7,0 m^3/m^2h
Air flow rate outside hours of operation (nights/weekends)	1,0 m^3/m^2h
Cold water distribution temperature for AHU	7 ºC
Hot water distribution temperature for AHU	35 ºC
Hot water distribution temperature for room units	45 ºC

Table 3.2: Input technical installation parameters

3.3 Energy supply system modelling

This section covers the explanation of how to make an early design and how to model in IDA-ICE the energy supply system. Zero emission buildings normally use a combination of renewable energy systems for the supply of heat and electricity, as presented in the table 2.2 of chapter 2.5. To decide different combinations, it is assumed in the beginning that heating systems will cover the demand for domestic hot water and space heating, while generation systems generate the required electricity. In office buildings where there is an important cooling demand, the system has to be adjusted to cover also that additional load. The generated electricity will be used first for self-consumption and the excess will be fed into the grid and sold to the local power company.

Heating and cooling systems in buildings are selected and designed based on load graphs. These graphs, also called duration curves, describe the heating and cooling consumption over time, making easier to visualize how supply technologies cover the year building demand. Thus, the system capacity is decided to cover a percentage of the demand, i.e. with a certain coverage factor. Thermal power demand diagram or heating load diagram represents the heat demand for space heating, heating of ventilation air and domestic hot water heating. As it has been represented in figure 3.22, this diagram is a sum of an average power demand for DHW and a power duration curve for space and ventilation air heating. This analysis will be made in an annual basis.

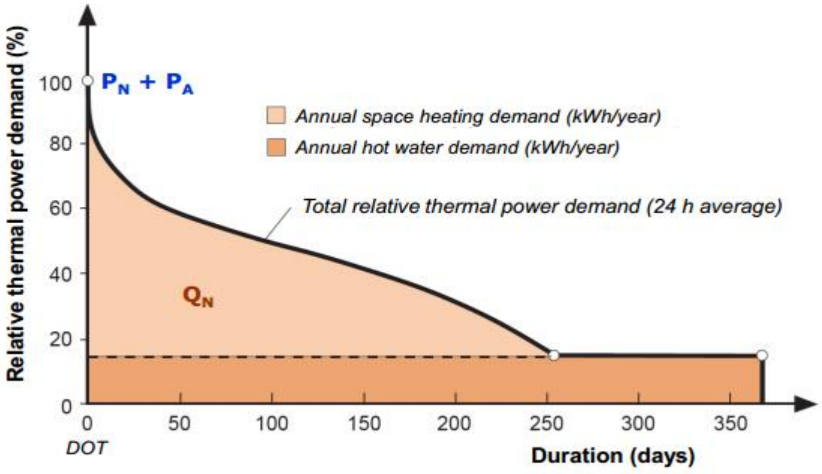


Figure 3.22: Heating load curve representation [37]

Unlike the previous study [14] made for residential buildings, this project seeks also to satisfy the cooling demand of the building. A typical office building needs space cooling due to various effects that contribute to increase indoor temperature: solar radiation through windows, conductive heat transfer through the building envelope and heat gains. This means that it is necessary to include the annual thermal power demand for cooling in the duration curve, as in figure 3.23. It should be pointed out as clarification that the cooling demand in this project only comprises cooling of ventilation air. The maximum cooling power demand occurs at the warmest day with sunshine/solar radiation. This value must be calculated from hourly values, like simulations in IDA-ICE.

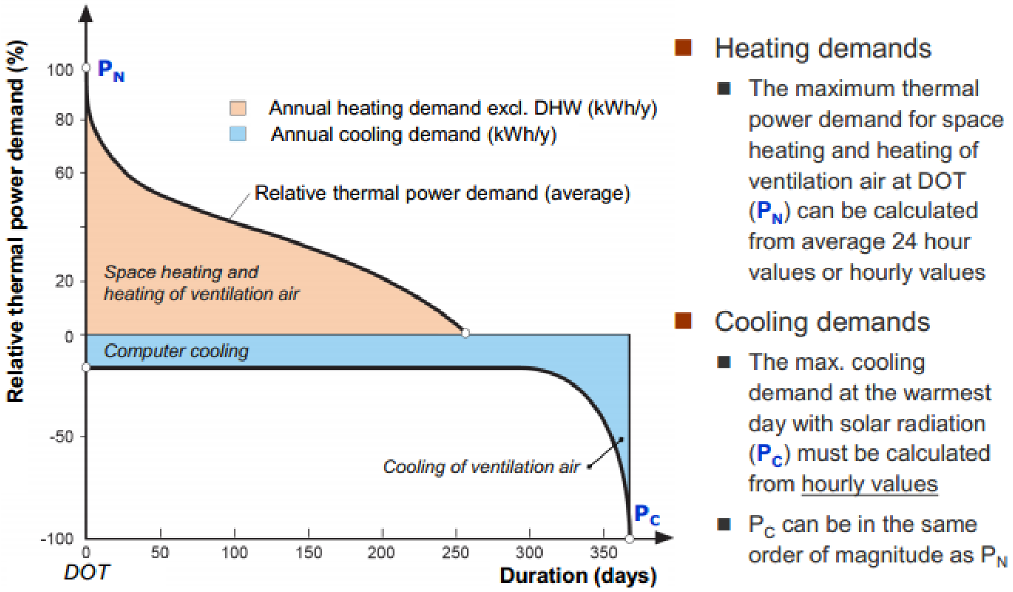


Figure 3.23: Thermal power diagram, heating/cooling [37]

Figure 3.24 gives the real heating and cooling load for the concept building used in this project. As the graph shows, energy supply systems should be sized to cover a heating peak load of 61 kW and a cooling peak load of 35 kW. In this particular case the heating load presents a really high and steep peak load representing the power needed to heat the building in the coldest days of winter. When deciding the supply system that is going to cover the entire demand, it is commonly used a combination of technologies in order to ensure a more efficient system. This is because if a unique system is sized to cover the whole demand, most of its power capacity will be wasted while the demand is changing during the year. For that reason, as general rule the diagram is divided in base and peak load, using different systems for each load part. A supply system with low operation cost covers the base load during the whole year, while a low investment system is covering the peak load that will occur during the period with higher demand, normally winter. Therefore the peak load is covered by a normal electric device, top heater in IDA-ICE, which gives the extra power for cold days. A normal way of working is to size the base load system where the slope steepness changes, around 15-25kW, and cover the rest with the peak load system. It should also be mentioned that the top heater has been limited to 30kW. Otherwise the electricity demand would have high peaks, what can be unsatisfactory for the interaction with the grid. It has been limited after checking that it has negligible effects on indoor temperature. On the other hand the cooling demand is entirely covered with a chiller, except with the case of a reversible heat pump installation, which will be explained in detail shortly. In this project six different base load systems are modelled and then combined with solar thermal and PV panels: district heating, air source heat pump, ground source heat pump, combined heat and power, bio boiler and electric boiler. Table 3.3 collects all different combinations that are simulated in cost optimal studies. The first cost optimal analysis studies each system with the entire roof covered by PV and a variable area of ST in the south façade; depending this area on the ST optimal sizing. A second analysis adds PV in the west façade to see how much more generation is realized and its effect on the final results. Unlike the area of installed ST, the PV system will have the same size for every system used in this project.

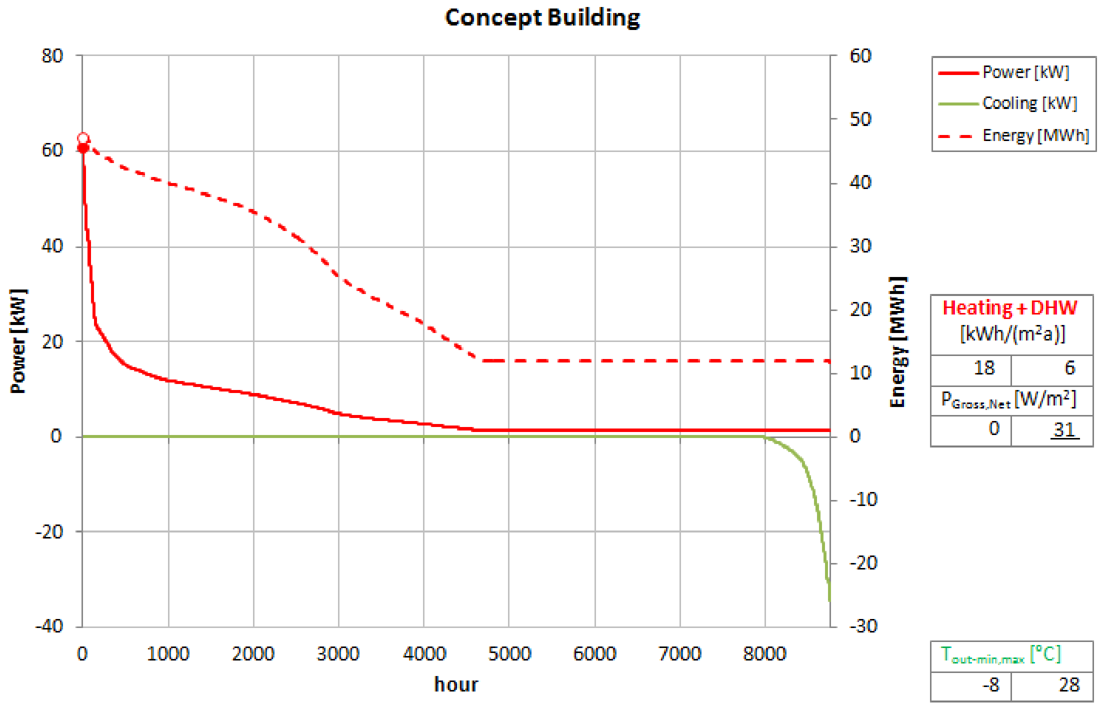


Figure 3.24: Heating and cooling load for the concept building

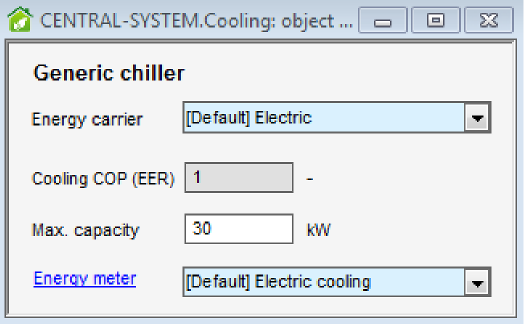
Base system	Peak system	Generation
District Heating (DH) + ST?	-	1-Roof PV 2- Roof PV + West façade PV
Bio Boiler (BB) + ST?	Electric heating (30 kW)	
Air Source Heat Pump (ASHP) + ST?		
Ground Source Heat Pump (GSHP) + ST?		
Combined Heat and Power (CHP) + ST?		
Electric Boiler (EB) + ST?	-	

Table 3.3: Combination of energy supply technologies

Following paragraphs explain how to define the main parameters of every energy supply system used for simulations. This part is especially focused on setting input parameters in the ESBO plant of IDA-ICE.

3.3.1 Chiller

Actually IDA-ICE offers two possible models to satisfy the cooling demand, a generic chiller with basic input data and a more complex brine to water chiller. Faced with the impossibility of simulating reversible heat pumps in IDA-ICE, a generic chiller is going be used to cover the cooling load. Even though it seems more realistic to use a more complex system to simulate the cooling mode of a reversible heat pump, it was not appropriate to use a brine-to-water model when there is no air-to-water chiller available in the software. A generic chiller is therefore defined with COP and maximum cooling capacity as input parameters. Its capacity is going to be limited to 30kW, but the cooling demand can go up to 35kW, because the difference is supplied by the cold tank. Both air source and ground source heat pumps have a different cooling power source, what will be explained in their respective sections. Cost data for a 30 kW chiller can be found in Appendix F. It should be mentioned that chillers are the same as brine-to-water heat pumps but working in cooling mode.



Generic chiller

Energy carrier: [Default] Electric

Cooling COP (EER): 1 -

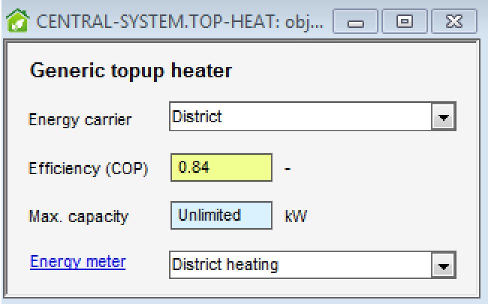
Max. capacity: 30 kW

Energy meter: [Default] Electric cooling

Figure 3.25: Generic chiller parameters

3.3.2 District heating

The district heating system is modelled in IDA-ICE like a generic top heater with unlimited capacity. In this case there is no need to use a peak load system because district heating is enough to cover the entire heating load. According to the standard NS3031, the system has an efficiency of 0.84 due to losses during the distribution. In the figure below there are input parameters for a district heating model. Approximate cost data for a district heating installation is given in Appendix C.



Generic topup heater

Energy carrier: District

Efficiency (COP): 0.84 -

Max. capacity: Unlimited kW

Energy meter: District heating

Figure 3.26: District heating parameters

3.3.3 Air Source Heat Pump

How to define all the parameters for a heat pump model in IDA-ICE has been well explained in chapter 3.1.2. For this study the ASHP has been sized with a capacity of 18 kW and a COP of 3.6. Unlike other energy supply technologies, heat pumps can provide cooling by themselves. Reversible heat pumps can work in both heating mode and cooling mode by switching the direction of the air flow. However IDA-ICE does not have any reversible heat pump system available. The only cooling device that can be introduced in the plant is a chiller. As it has been said before, a generic chiller was the only possible option to try to reproduce the cooling mode of an air source heat pump. Hence, the generic chiller is working as an evaporator in cooling mode. Its capacity is defined with a capacity relation between condenser and evaporator, following the equation:

$$Q_e = \frac{Qc}{1.3} \qquad \text{(Equation 3.3)}$$

So for an 18 kW heat pump, the generic chiller will be sized with 13.85 kW. Apart from that, the cooling seasonal performance factor (SPF) is calculated to dimension the COP of the chiller. This parameter is especially used to measure the efficiency of an air source heat pump, and it is related with the COP. Moreover, it can be seen that the cooling capacity of the reversible heat pump is not enough for the building's demand, so the system needs an additional chiller in order to cover the rest of the power. This chiller will be sized with a maximum cooling capacity of 18 kW; cost data for calculations is in Appendix F. Thereby, both the chiller and the reversible heat pump working in cooling mode will cover the entire cooling need during the summer period.

SPF calculation

The higher the SPF rating of a heat pump unit, the more efficient it is. The seasonal performance factor is calculated like the amount of cooling produced divided by the electrical power consumed during the season. The first step for the calculation is to extract the COP values for different outdoor temperatures from a manufacturer's cooling mode curve. Once the cooling demand of the building has been obtained, each hour of the season will have its cooling power demand, outdoor temperature and COP. The compressor of the heat pump is the device that consumes electrical power during the operation, so the compressor power should be calculated using equation 3.5. Then, the cooling produced during the season is the sum of the hourly cooling power, while the electrical power consumed is the sum of the hourly compressor power, equation 3.6. COP curves used in this project have been obtained from an air source reversible heat pump unit given by Dimplex, shown in Appendix G. After performing manually the SPF calculations in an Excel file, the final COP set in the chiller is 4.86.

$$Q_{comp} = \frac{P_{cool}}{COP} \qquad \text{(Equation 3.4)} \qquad SPF = \frac{\sum(P_{cool})}{\sum(Q_{comp})} \qquad \text{(Equation 3.5)}$$

3.3.4 Ground Source Heat Pump

Like for the ASHP, the GSHP model has to be defined as explained in chapter 3.1.2. In reality a heat pump should be dimensioned calculating the optimum coverage factor (β_{opt}). Nevertheless, since this project is working in an early design phase, this value will be approximated. Sizing the ground source heat pump in the inflection point of the heating curve, it should have approximately a capacity of 18 kW. This is a reversible heat pump connected with a ground source borehole loop, which is a group of buried pipes that extract natural heat energy from the ground. The ground heat exchanger makes that the ground source heat pump has a higher COP than the air source heat pump, 4.3 in this case.

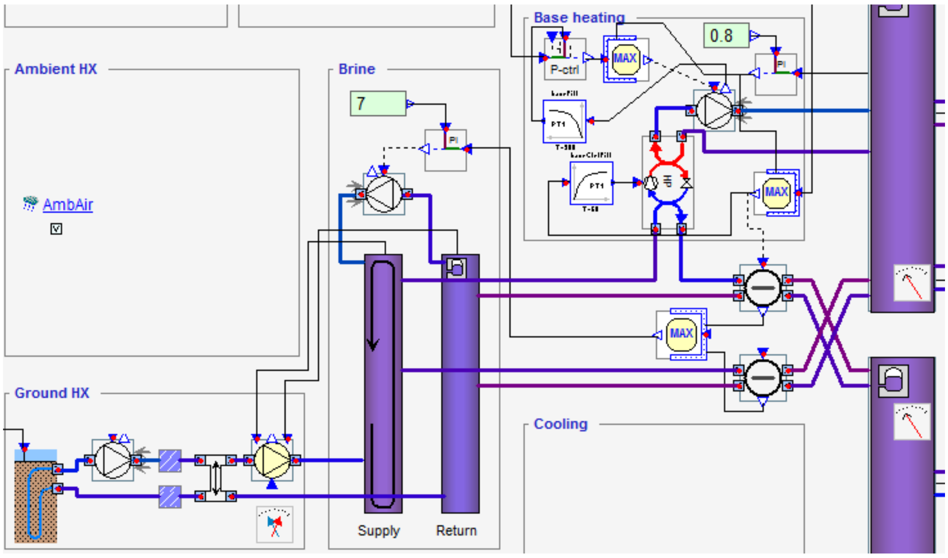


Figure 3.27: Ground source heat pump model in IDA-ICE

Vertical ground loops consist in a group of U-shaped pipes inserted into boreholes extending 100m below ground, with a mix of fluids circulated through the pipes. To estimate the total borehole depth needed, the theory says that this value is dependent on the power extraction per metre of borehole. The colder the climate, the lower the heat extraction rate, normally between 25-45 W/m. This project uses a fictitious building, thus this parameter is unknown. A rule of thumb for this kind of studies is to use 20 m borehole depth per kW of heat pump installed i.e. an 18 kW heat pump would require 360 m depth borehole. So it has been implemented as three 120 deep boreholes. As image 3.28 shows, they work as a ground heat exchanger, extracting heat during the heating season and cold during the cooling season. Their implementation accordingly provides free cooling for the ventilation cooling coil, in this way the cooling demand is satisfied without spending energy. The cooling power extracted from the ground is enough to cover the entire cooling demand. Besides, there is no need to install a cooling chiller because the ground heat exchanger is directly connected with both tanks through the brine system, illustrated in figure 3.27.

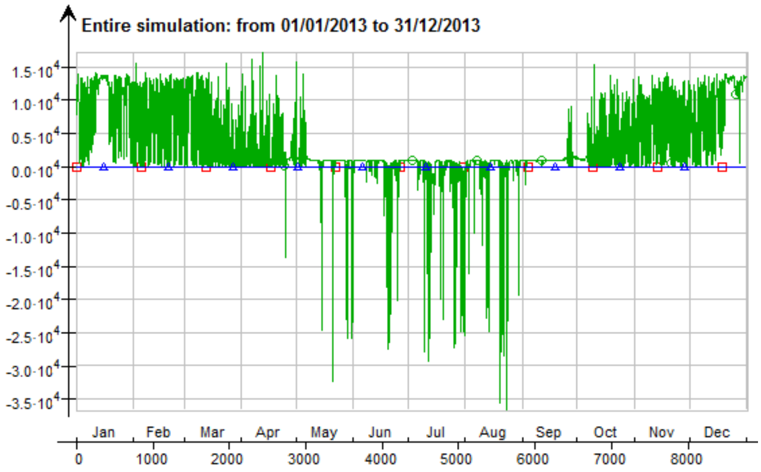
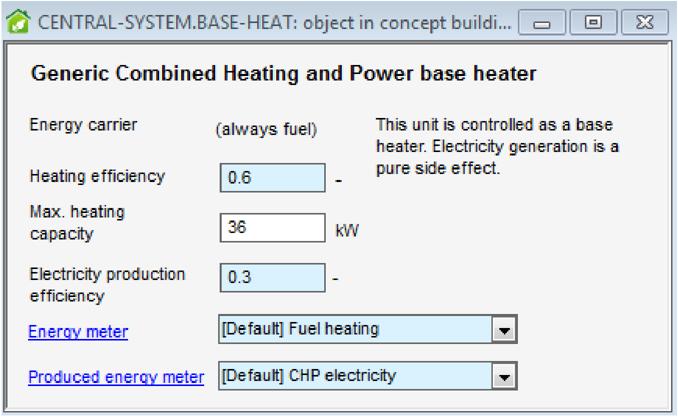


Figure 3.28: Ground heat exchange

3.3.5 Combined Heat and Power

In most European countries natural gas is used to run CHP systems. Nevertheless, an alternative source should be used in Norway because it lacks this natural resource. For micro-CHP, both Stirling and Rankine have potential, but the only commercially available product is the Stirling engine [20]. A biomass CHP using pellets as energy source is the alternative chosen for this study. It is sized with a maximum capacity of 18 kW according to the correct sizing in the heating load. Standard efficiencies of 60% for heating and 30% for electricity production have been used, giving an overall efficiency of 90%.


CENTRAL-SYSTEM.BASE-HEAT: object in concept buildi...

Generic Combined Heating and Power base heater

Energy carrier (always fuel)

This unit is controlled as a base heater. Electricity generation is a pure side effect.

Heating efficiency 0.6 -

Max. heating capacity 36 kW

Electricity production efficiency 0.3 -

Energy meter [Default] Fuel heating

Produced energy meter [Default] CHP electricity

Figure 3.29: Combined heating and power parameters

One critical point when dimensioning energy supply systems has been to realize that in version 4.51 of IDA-ICE the model for the boiler/CHP does not work properly in combination with an electric top heater. Simulations show that the base heating system mostly works at half maximum capacity even with very a high energy demand. This is because when the top heater is activated, it enters into action instantaneously using all its power and not allowing the base heating system to reach its maximum capacity. This is an undesired effect of the control logic of IDA-ICE, because in normal conditions the program should use first the base heating system until it reaches its power limit, and then, activate the top heater when there is a need for higher heating power. This problem only appears with boiler/CHP models, while the program works correctly with heat pumps. Since the model was working at half maximum capacity, a previous study considered as an acceptable solution to double the system capacity, so it can work nearer to the real maximum power.

At this point, it was questioned whether it is right to limit the capacity of the top heater or not. When the top heater has limited capacity, it enters into action before the base heating reaches its maximum capacity, like it has been explained. But when the top heater reaches its limit in high heating demand hours, the program uses the base heating again to cover the remain demand. So if the base heating system is dimensioned with a double capacity of 36 kW and with a limited top heater, results show that the boiler is in the reality working with peaks above the real wanted capacity of 18 kW, illustrated in figure 3.30. This is especially problematic in the CHP model, which also gives a higher electrical generation. If an unlimited capacity top heater is installed instead, some of those peaks are cut because IDA-ICE can use the top heater to cover high demands. However, define an unlimited top heater does not solve the double capacity error and it compromises the results from the point of view of grid interaction, due to the emergence of high peaks in the electricity demand. Hence, it has been finally decided to maintain a limited top heater and keep working with the error in the boiler performance. Software developers are responsible to solve the wrong operation of the control logic for boiler/CHP models. The cost data for cost analysis is given in Appendix D.

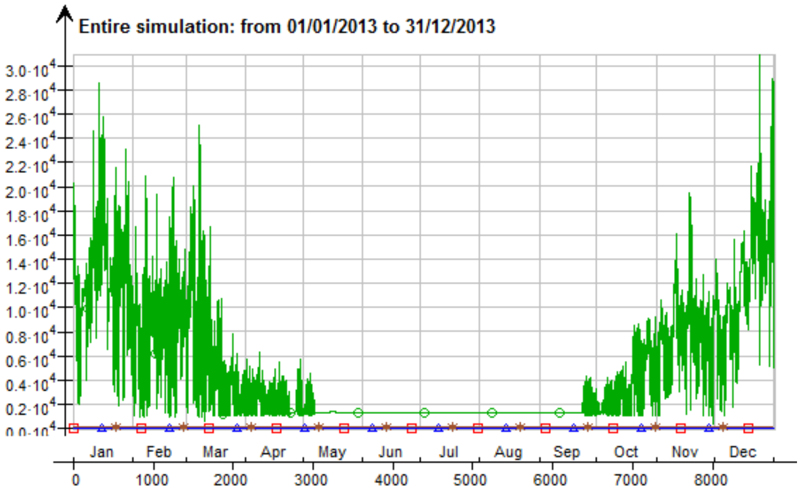
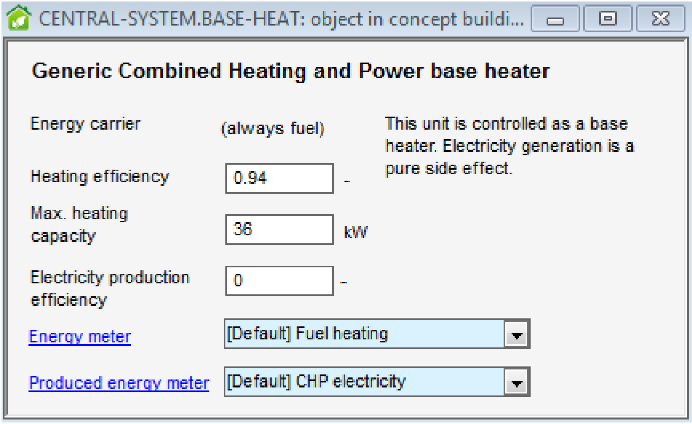


Figure 3.30: Bio Boiler performance using a maximum capacity of 36 kW

3.3.6 Bio Boiler

There are no bio-boilers available in the selection of energy supply systems in IDA-ICE. The only way to simulate a bio boiler is to use a CHP model with 0% electricity production efficiency. The biomass boiler will be run with pellets as energy source. The boiler used for simulations has 18 kW of maximum capacity and 94% efficiency. When defining the bio-boiler capacity, it should be over dimensioned with double capacity as explained before. The cost data and technical data are given in Appendix C.



CENTRAL-SYSTEM.BASE-HEAT: object in concept buildi...

Generic Combined Heating and Power base heater

Energy carrier (always fuel)

This unit is controlled as a base heater. Electricity generation is a pure side effect.

Heating efficiency 0.94 -

Max. heating capacity 36 kW

Electricity production efficiency 0 -

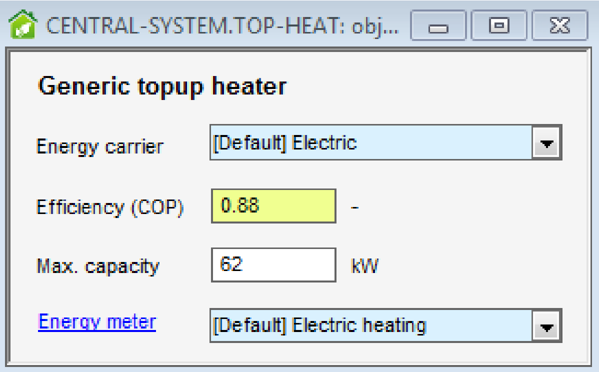
Energy meter [Default] Fuel heating

Produced energy meter [Default] CHP electricity

Figure 3.31: Bio boiler parameters

3.3.7 Electric Boiler

An electric boiler is included in the study, so normally used renewable technologies can be compared with one completely fed by electric energy. Norway is a country characterized by a low energy price, so it seems a good idea to show what happens if the building has an entire electricity demand. The electric boiler has been sized with 62 kW and an efficiency of 88%, in that way it is able to cover the entire heating load. Cost data can be found in Appendix F, which is information taken from a Norwegian manufacturer. Apart from the electric boiler used as base heating system, most of the other systems need a small electric boiler as backup to cover the peak heating load in winter.



CENTRAL-SYSTEM.TOP-HEAT: obj...

Generic topup heater

Energy carrier [Default] Electric

Efficiency (COP) 0.88 -

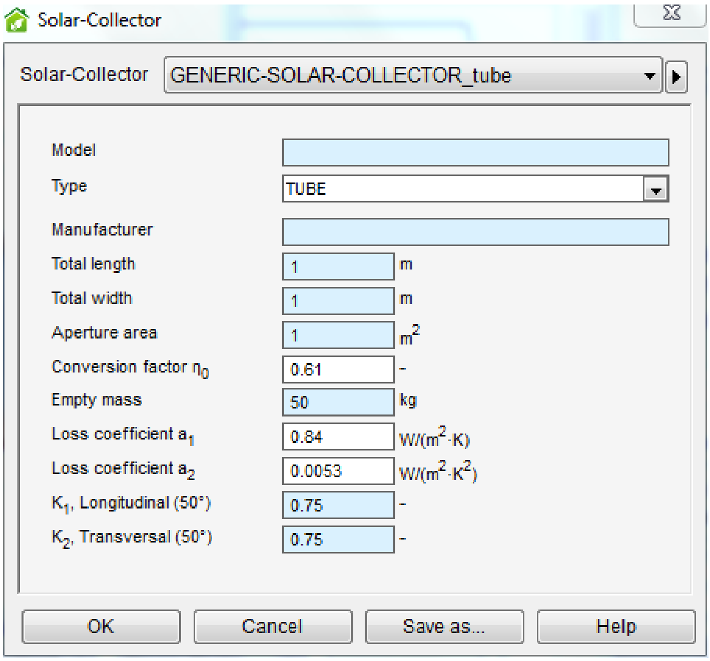
Max. capacity 62 kW

Energy meter [Default] Electric heating

Figure 3.32: Electric boiler parameters

3.3.8 Solar Thermal

In this project the PV system is covering the whole roof surface, so solar thermal collectors have to be installed in the south façade. The ST system is positioned with a 90º tilt angle and a variable area depending on ST optimization results. Vacuum tubes have been used due to their lower heat loss compared with flat plates. Flat plates usually have a larger optical efficiency than vacuum tubes, but in return the heat loss is less for vacuum tubes. Therefore vacuum tubes are usually preferred in colder climates and for hot water production. All the parameters and costs have been defined according to the model CPC9+ provided by SGP Varmeteknikk AS. The cost data and technical data are given in Appendix D.



Solar-Collector: GENERIC-SOLAR-COLLECTOR_tube

Model		
Type	TUBE	
Manufacturer		
Total length	1	m
Total width	1	m
Aperture area	1	m^2
Conversion factor η_0	0.61	-
Empty mass	50	kg
Loss coefficient a_1	0.84	$W/(m^2 \cdot K)$
Loss coefficient a_2	0.0053	$W/(m^2 \cdot K^2)$
K_1, Longitudinal (50°)	0.75	-
K_2, Transversal (50°)	0.75	-

Figure 3.33: Solar thermal collector parameters

3.3.9 Photovoltaic

This project considers in a first approach to cover the entire flat roof with PV panels, calculate the amount of energy generated and see how far the building is from the net ZEB balance. Before the installation of solar panels in a roof, the user should study and simulate the system according to solar radiation, weather conditions, available space and possible shades. In Norway, the optimum tilt angle (β) for a system facing south is around 30-40 degrees. Although that is the best position to optimize electricity production per panel, it is not for the whole system. Northern countries have a low solar height during the year, so if the aim is to install as much panels as possible a high tilt angle will lead to self shading in a flat roof. A way to solve this problem is to install them with a lower tilt angle, normally between 10-20 degrees, in a north-south or east-west orientation.

To be sure which is the orientation with higher electricity production some simulations have been performed in IDA-ICE using different low tilt angles. In IDA-ICE PV is really simplified, so it can be dimensioned setting only total PV area, efficiency, position and tilt angle. Since it is not possible to define a system based on arrays, the program is unable to simulate shading between panels. IDA-ICE only allows modelling PV systems as a bloc of panels facing one direction in each simulation. Therefore, if considering a double oriented system, two separate simulations must be done and added together. For the calculations, a 70% of the roof will be covered with panels, leaving the mandatory free space for maintenance operations as well as space in the borders. This means that in a 495 m^2 roof, 173 m^2 of panels facing each orientation will be installed, a total of 346 m^2. Besides that, an annual efficiency of 17.9% has been defined for the system.

Tilt angle	**Orientation**	**Electricity production**	**System total production**
10º	East	22462 kWh	**46066** kWh
	West	23604 kWh	
	North	20319 kWh	46036 kWh
	South	25717 kWh	
20º	East	21816 kWh	45700 kWh
	West	23884 kWh	
	North	17623 kWh	45548 kWh
	South	27925 kWh	
40º	South	30420 kWh	-

Table 3.4: Analysis performed in IDA-ICE showing the PV electricity production in different orientations.

As the table 3.4 shows, the East-West oriented system with 10º tilt angle is the one that provides greater amount of electrical generation. Apart from that, East-West PV systems have some additional advantages comparing with North-South systems as they fed-in more energy during morning and evening, therefore reducing peak loads and thus relieving the grid. The electricity production will also fit better with occupant schedules, increasing the amount of self-consumed electricity. A low tilt angle gives the possibility to install more panels per square meter, allowing a higher production. Moreover, due to the sharp drop in module prices, it seems that an increased demand for this kind of systems is expected.

Three different PV alternatives with their corresponding cost data are given in Appendix G. The alternative selected for this project is the module of REC with Eltek inverter. As mentioned before, every system will use the same area of PV, so there is not any special reason for the selection. Nevertheless in a real study, the type of PV modules selected is a very important factor because it will determine whether the building reaches the ZEB level or not.

3.4 Economic parameters

In this chapter how all the necessary economic data for cost analysis has been obtained will be discussed. On the one hand prices for each energy carrier used in the analysis are needed; electricity, district heating and pellets in this particular case. Oslo region will be used as a reference to obtain these values. On the other hand economic parameters for global cost calculations should be decided, namely discount rate, inflation and price escalations.

3.4.1 Electricity price

Understanding how the Norwegian power sector works is a necessary condition to be able to establish a real electricity price for the calculations. First of all, it should be noted that the Nordic countries have a connected power system, so their systems are mutually dependant [38]. The power sector consists in a large number of companies in charge of generation, transmission, supply, distribution and power exchange. Electricity is traded between different market players and organised by the Nordic power exchange, Nord Pool Spot. This trading company, which runs the largest market for electrical energy in the world, is owned by the Nordic transmission system operators. One of them, Statnett SF, is the national transmission company of Norway owned by the Norwegian government [39]. Therefore, the electricity price is determined in a market based on electrical conditions not only in Norway, but in the whole Nordic region. Temperature and weather conditions have for example a strong influence in the electrical demand, especially in Nordic countries, which also affects the power price. The market price varies over time; in fact, Nord Pool changes the value every hour.

As an electricity producer, a zero emission building user will be regarded as a plus customer. A plus customer is a producer of electricity that normally has a lower annual production than consumption and feeds the surplus electricity during certain periods to the grid. How producers buy and sell electricity is subjected to Norwegian regulations.

Plus customer

To facilitate the exchange of energy between end-users and grid, the Norwegian Water Resources and Energy directorate (NVE), published in 2010 the general dispensation for plus customers [42]. NVE is the organization which regulates the Norwegian electricity and district heating market. This general dispensation enable plus customers to feed more easily their surplus power into the grid. First of all, it states that the local area license holder buys excess power from the plus customer disregarding the balance agreement with Statnett. Regulations before NVE’s dispensation obliged all power producers regardless of size to make a balance agreement with the Norwegian transmission system operator for access to trade in the wholesale market for electricity. However, the scheme says that plus customers do not have access to sell electricity in the wholesale market, the sale will be directly agreed with the local power company. Additionally, the chapter § 4-2 of the Norwegian energy regulation [43] establish that entities taking part in power generation and distribution activities must have a trading license. With the plus customer regulation, they may be exempt from the requirement of having a trading license. These two were the main obstacles for end-users who want to be plus customers.

With respect to the electricity price, the document says that it should reflect the market price of the area. As explained before, the price determined by Nord Pool Spot varies unpredictably depending on the supply and demand. Norway is currently split into five different price zones, shown in the Nordic power market bidding shown delimitation [44], so the spot price will change in accordance with the region.

Plus customers will be billed with an amount of money related with the hours of power withdrawal, subtracting to this an amount depending on the hours feeding to the grid. The price of the surplus production is stipulated in a separate agreement between the local power company and the individual plus customer. The company buying the excess electricity to the plus customer will pay a price according to the Nord Pool Spot price. Apart from this initial price attached by the market, the local power company shall pay an additional fee to the plus customer who feds electricity in compensation for the reduction of losses in the local grid. On the other hand, the current regulation for network operation and tariffs [45] stipulates that customers with a regular withdrawal distribution will be charged with a fixed annual amount and a power dependant amount, what is called grid tariff. The fixed term covers the customer costs, while the energy dependant term covers the loss caused by the customer due to the extraction from the grid. The energy component, also known as energy tariff, will be further differentiated according to the minimum requirements set out in the Control Regulations § 14-1, i.e. winter day, winter night/weekend and summer [42]. In the table 2.1 it is possible to see an example of how the electricity tariff for a plus customer is calculated. The data are taken from Hafslund [46], the owner of the power grid and district heating network in Oslo.

Plus customer tariff	Annual fee [NOK/yr]	Energy tariff [NOK/kWh]		
		Winter day Sept-Apr	Winter night/weekend Sept-Apr	Summer May-Aug
[1] Grid tariff (Withdrawal from the grid)	750	0,3865		0,3625
[2] Feed-in, compensation	-	-0,043	-0,064	-0,064
[3] Feed-in, electricity price	-	Price from Nord Pool Spot		

1) These seasonably variable prices refer to private customers with annual energy consumption in excess of 8000 kWh. They are presented inclusive of VAT at the rate of 25%, a 0.01 NOK/kWh statutory contribution to the Enova energy fund and electricity consumption tax of 0.116 NOK/kWh. (Use 0.376 as energy tariff)

2) Compensation for the reduction of losses in the local grid.

3) Local power companies buying electricity to the plus customer pays the current price at Nord Pool Spot.

Total price

Considering all the information, it is possible to determine the total electricity price that will be used in the calculations. The initial electricity price, as it has been done in [14], is an average spot price in the bidding area of Oslo over the last three years is used, giving a price of 0.29 NOK/kWh [40]. Some additional charges should be included to this price, like the general Value added tax (VAT) or tax in the purchase price, which is a 25% in Norway. In addition, electricity suppliers and some end-users of electricity are obligated by law to buy electricity certificate corresponding to a certain proportion of their electricity sales or usage [41]. This certificate, which aims to help renewable electricity production, means 0.017 NOK/kWh which should be added to the initial price. Finally as explain above, an energy dependant charge should be included, which will vary between summer and winter.

El-price

Winter	$\mathbf{0.29 + 0.29 * 0.25 + 0.017 + 0.3865 = 0.766}$ [NOK/kWh]
Summer	$0.29 + 0.29 * 0.25 + 0.017 + 0.365 = \mathbf{0.7445}$ [NOK/kWh]

El-price exported (income)

Winter	$\mathbf{0.29 + 0.29 * 0.25 - 0.043 = 0.3195}$ [NOK/kWh]
Summer *	$0.29 + 0.29 * 0.25 - 0.064 = \mathbf{0.2985}$ [NOK/kWh]

* Summer and weekends/nights in winter

3.4.2 District heat price

Until this point, Oslo has been used as a reference region for the study. When searching for the DH price in the supply company in Oslo, Hafslund, it has been found a different way of accounting the price. Hafslund uses an element on the basis of measured power per month (NOK/kWh/month) and a component on the basis of energy (NOK/kWh) [49]. Since for the current calculations it is necessary to use a price only dependant on kWh consumed, another company will be used. Like in [14] BKK, supplier of district heating in Bergen, is the company chosen to set the reference district heating price, the same company will be used. As this project studies a concept building and not a real building in a specific area, this change can be done. The price set by BKK for small business customers is the sum of an energy rate price and a transfer of district heating price. The first part follows the market price for electricity determined by Nord Pool and it is calculated as a weighted average of the spot during the consumption period. For this part the same spot price as in the electricity price (minus the electricity certificate) will be used, so a value of 0.362 NOK/kWh. Transfer of district heating price is regulated in accordance with the applicable tariffs for energy measured plant (BKK Nett AS) and applicable government taxes. From 1 January 2014 this price is 0.293 NOK/kWh [50]. Summing both prices result in a total District heating price of **0.655 NOK/kWh**. There is also an annual fixed amount of **3000 NOK/yr** that has to be taken into account in the cost optimal calculation.

3.4.3 CO_2 emissions price

A macroeconomic cost-optimal calculation requires establishing prices for CO_2 emissions. Long-term CO_2 price development estimations are given by the cost-optimal regulation [18]. The projections assume a price per tonne of 20€ until 2025, 35€ until 2030 and 50€ beyond 2050. The excel file used for cost-optimal calculations was defined with a money rate change of last year, namely 7.443 NOK/€. However this value is constantly changing, even if now is above 8 NOK/€.

3.4.4 Pellets price

Wood pellet production in Norway is based on residues from wood processing industries [52]. Pellets can be bought in small bags which are collected by the customer, big bags with a higher weight or as bulk pellets for large customers. Bulk pellets are usually sold by the ton transporting loose pellets with a lorry. This project assumes the use of bulk pellets basically due to a lower price. It is difficult to estimate an actual average price in the Norwegian market because of the lack of available information. Thus it is taken the same value of 0.359 NOK/kWh excluding VAT previously used in [14]. By adding the Norwegian VAT of 25% the price for domestic bulk pellets becomes **0.45 NOK/kWh**. The price is continuously changing like it can be seen in figure 3.34, the graph that shows the evolution of pellet prices for industrial purposes in Nordic countries.

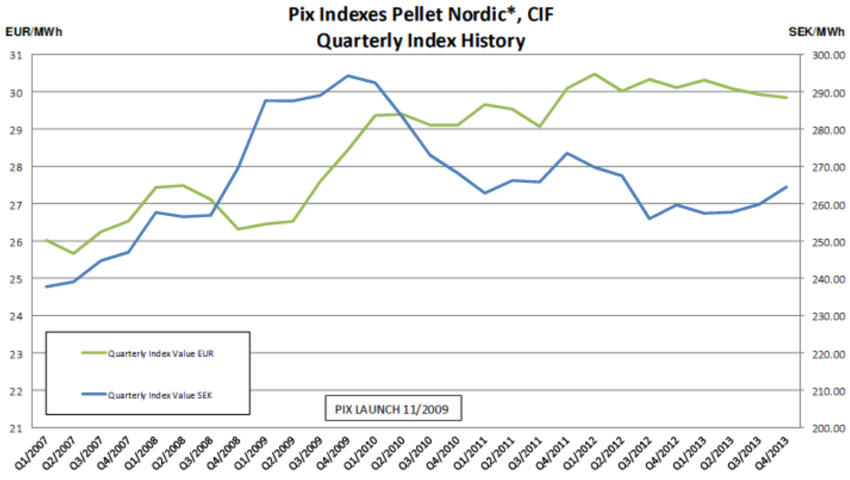


Figure 3.34: Pellet price evolution in Nordic countries [53]

3.4.5 Discount rate and inflation

Continuing with the economic parameters and according to handbook of socio-economic analysis of energy projects by NVE [47], the nominal discount rate applied in this project will be 6%/yr. The handbook particularly suggests using a 6%/yr discount rate for energy projects with energy efficiency measures with a clear environmentally friendly advantage, and 8%/yr in other case. For that reason, the selection of renewable energy systems for ZEBs, which implies all kind of efficiency measures, will use the first value. Besides, the increase in the general price level of goods and services in an economy, better known as inflation, is an annualize percentage that changes in a general price index over time. An inflation rate of **2.1%/yr** corresponding to the month of February 2014 will be used in the calculations [48]. By using the equation 2.18, the real discount rate becomes **3.82%/yr**.

3.4.6 Price escalation

Price escalation rate is defined as the price change of a specific good of service. The escalation will tend to be more or less equal to the inflation rate, but when technology or efficiency changes are applied in market this can change. Since cost optimal methodology is a long term study, estimated energy price developments trends are needed for the calculations. It is therefore necessary to define a specific price escalation rate, as an average increase of the electricity price per year. Following the document "Implementing cost optimal methodology in EU countries" [51], three different scenarios with different rates will be analyzed. A basic scenario will be study first, using a rate of **2.8** %/yr. For a subsequent sensitivity analysis a lower price escalation of **1.3** %/yr and a higher one of **4.3** %/yr will be also used. A high energy price development means that the net present value of future energy costs increase compared to the basic scenario, while a low energy price means the opposite.

Economic parameter	Value
Price escalation	0.028/0.013/0.043
Real discount rate	0.038
Inflation	0.021
Electricity price	0.766 NOK/kWh (Winter value)
Pellets price	0.45 NOK/kWh
District heating	0.655 NOK/kWh
Electricity price (exported)	0.298 NOK/kWh (Summer value)

Table 3.5: Input economic parameters for cost optimal calculations

4. Results

This chapter aims to present the cost optimal methodology results in an early design phase for the concept office building. Following the methodology presented in chapter 3.1 and deciding all the parameters, as done in later sections of chapter 3, it is possible to decide the best energy supply system for the building. These results will serve as an example for future studies of energy supply selection that want to include, as in the office building case, the cooling demand. Six different base heating systems have been compared and analysed.

Initially, solar thermal optimization calculations are presented, where the total size of solar collectors is decided according to the profitability of each system. ZEB balances, monthly electricity charts and other graphs are obtained, nevertheless only these first two will be presented and compared because of their importance for a further discussion. Once all the consumptions, technology costs and energy prices are identified, it is the moment to perform cost analysis calculations. Afterwards global costs for each system are simply compared in both graphs for a financial and macroeconomic perspective, i.e. with and without CO_2 emissions cost. In addition, two final graphs make a final comparison sorting each system after considering global costs and weighting factors, the first graph CO_2-eq emissions for each energy supply and a primary energy balance graph for the second one.

4.1 ST optimization results

An excel file is created for each energy supply system studied. Tables for weather data and solar thermal data are identical for all the energy supply systems, whereas the total heating and cooling table is required to be copied and pasted from IDA-ICE results. The amount of energy use for heating purposes with different energy carriers along with the price of each carrier, is what finally defines the substitution price, and consequently the decision of whether it is better to install ST or not. Looking table 4.1, it can be appreciated that the office building does not require a great amount of solar thermal collectors, even for systems that consume more. With both heat pumps and biomass boilers it is better not to use them because energy saving do not compensate the investment of their installation. What these systems have in common is a low substitution price. Heat pumps are very efficient systems with electrical energy consumption, which normally is not very high, thus it is cheaper to use only the heat pump rather than installing an additional ST system. For the biomass boiler, even if it gives a higher consumption, it uses pellets that have a low price per kWh compared with other carriers. District heating, CHP and electric boiler results say that ST can be installed, but the optimal area is rather small. The electrical boiler needs the higher optimal ST area due to its high electrical consumption. Small areas are translated into small solar fractions, so the total heating energy fraction covered by the ST is not going to be very high.

Energy supply	**Substitution price [NOK/kWh]**	**Optimal ST area [m^2]**	**Total Savings [NOK]**	**Solar fraction**
District heating (DH)	0,77	7	1843	0,05
Air source heat pump (ASHP)	0,32	0	0	0
Ground source heat pump (GSHP)	0,24	0	0	0
Combined heat and power (CHP)	0,75	5	547	0,04
Biomass boiler (BB)	0,5	0	0	0
Electric boiler (EB)	0,87	13	8747	0,09

Table 4.1: ST optimization results

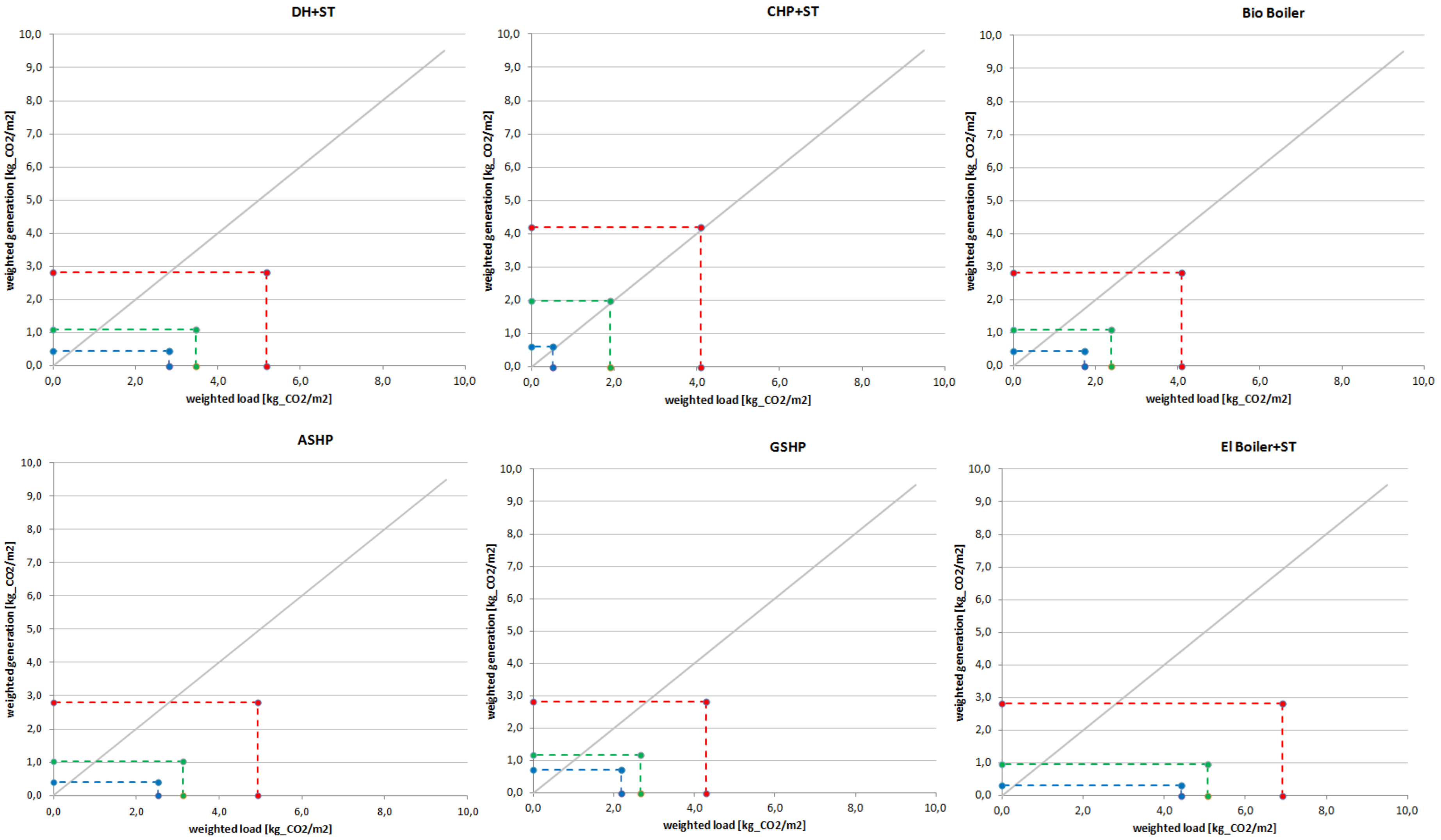
4.2 Output graphs

The excel file where simulation results are collected, give some output graphs in connection with the ZEB balance concept. Those shown in following pages have been regarded like the most suitable to compare energy supplies. The ZEB balance is basically a mathematical representation of the supplied energy to the grid compared with the energy consumption of the building. How to put the NZEB theory into practice can be properly understood by presenting only three graphs.

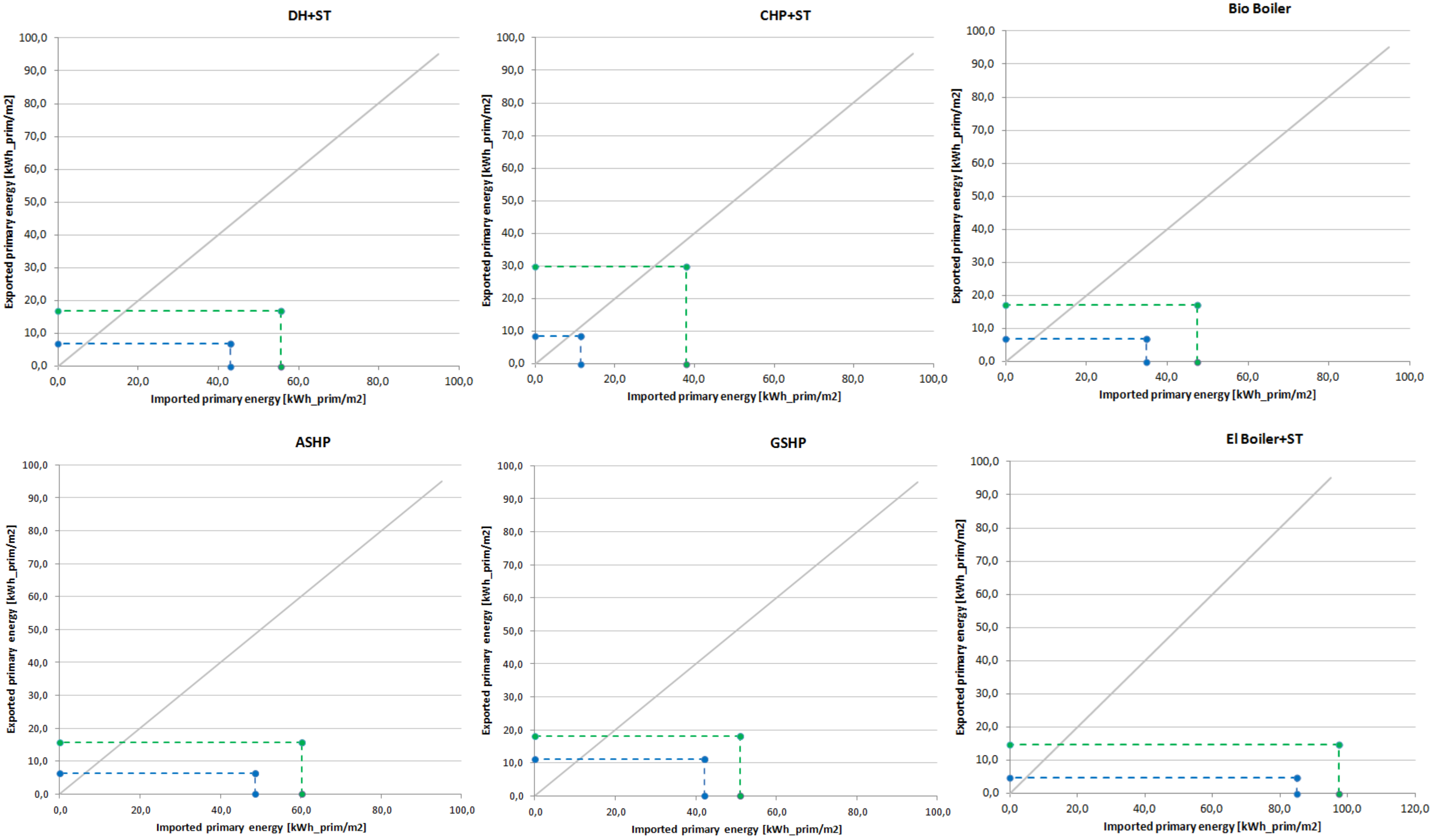
The first two pages illustrate the balance representation using both types of weighting factors for each base heating system. In the CO2-eq emissions balance the three possible balances described in chapter 2.1 have been calculated and presented in different colours. A dotted red line gives the load/generation balance, a green one the imported/exported balance and finally a blue line the monthly net balance. Moreover, the primary energy balance excludes the load/generation balance and only shows the other two. Data used for further cost calculations only include imported and exported energy values, so there is no need to obtain the load/generation balance which is a calculation from a more simplified point of view.

Besides, it seems convenient to show a graph that also takes into account the interaction between grid and building. This graph, called electricity month chart, is a simple representation of the electricity load and the amount of generated electricity by on-site systems throughout the year. So it is good way to visualize the mismatch between both of them. The ability of the generation system to match the electricity load is a key concept for ZEBs, and it is also determinative for the amount of self-consumption. It is important to remember that self-consumed electricity makes the difference between balances, in relation with the other two graphs. This project does not aim to perform an analysis in terms of electrical mismatch, but it should be kept in mind that this will be an essential point in future analysis.

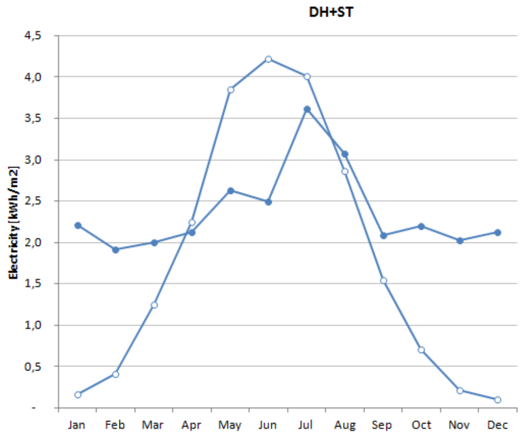
ZEB balance graph (CO2-eq emissions)



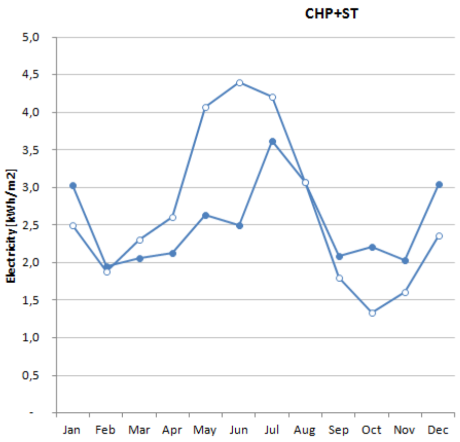
ZEB balance graph (PEF)



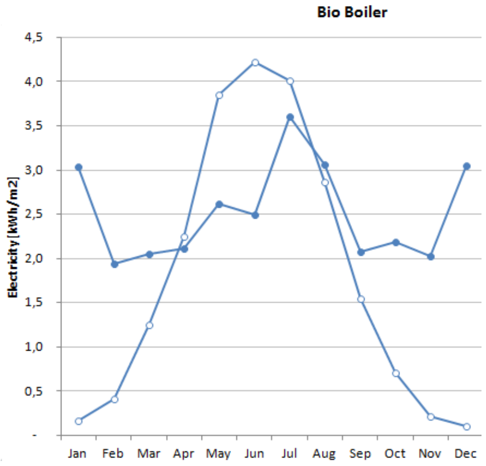
Electricity month chart

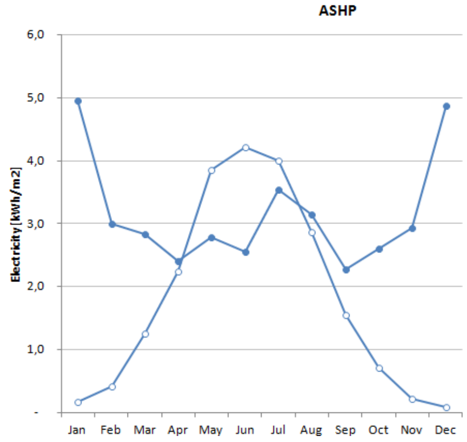


mismatch factors	
monthly	hourly
load match	
64%	46%
unmatched generation	
16%	39%
carrier surplus	
0%	0%
export/import power ratio	1,0

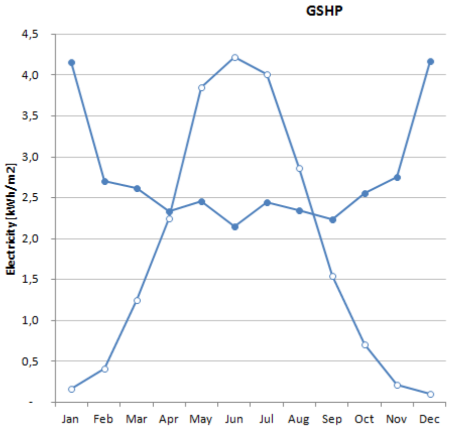


mismatch factors	
monthly	hourly
load match	
91%	56%
unmatched generation	
15%	48%
carrier surplus	
6%	6%
export/import power ratio	1,0

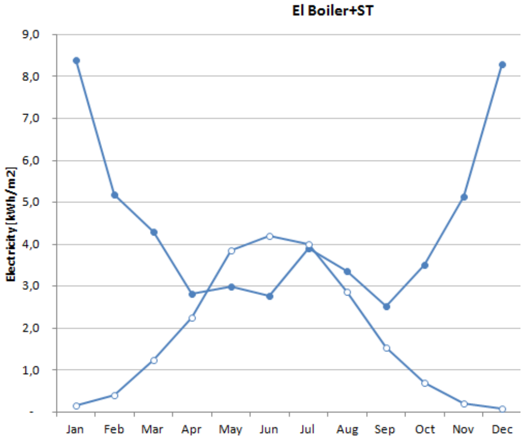




mismatch factors	
monthly	hourly
load match	
49%	36%
unmatched generation	
15%	36%
carrier surplus	
0%	0%
export/import power ratio	0,8



mismatch factors	
monthly	hourly
load match	
49%	38%
unmatched generation	
26%	42%
carrier surplus	
0%	0%
export/import power ratio	0,8



One of the first things that can be drawn when looking throughout the graphs is that most of the systems used in the analysis give as a result a nearly zero energy building. Each energy supply technology but the CHP, give a balance point below the NZEB balance line. The fact that the building does not reach the level of ZEB can be explained from different point of views.

On the one hand every system have been set with a fix PV area, this means that the approach for the study is to cover the entire roof with PV and see how far the building is from the balance line. Thus, it seems that there is not enough with the roof area provided for PV production; therefore more PVs should be installed in the façade to transform the building in a ZEB. Furthermore, if the main objective had been to obtain a ZEB, there would have been another approach to address the analysis. This alternative method is based on calculating first the PV area needed by each system to reach the balance line and then use different areas for cost analysis.

On the other hand it is also possible to obtain a ZEB by reducing to a greater extent the energy demand of the building. Current studies use passive house standards and technical codes to determine the efficiency of buildings, so internal parameters are set with the corresponding standards. This analysis is performed in a concept office building that serves as an example of how a low energy building should be, using in this case those standards. However, as investment increases, technology efficiencies will continue to improve, so regulations and market demands will ideally result in lower energy loads.

A more in depth study of system position in presented graphs is done. It seems that those systems which are nearer to the balance are characterized by using pellets as energy carrier (CHP and Bio Boiler) or having a low electrical consumption (heat pumps). Although heat pumps apply electrical factors, which usually are higher than the others, they are well positioned in the graph due to their low consumption. Apart from that, both have lower cooling consumption than the others. The ASHP system covers a part of the cooling demand with its efficient cooling mode, while the GSHP uses directly free-cooling from the ground, what makes the difference in the imported energy value between both technologies. Pellets have a low primary energy factor and CO_2 factor, so even if energy consumption is high, final weighted values will result in lower imported energy or weighted load. CHP+ST is aside the only system that reaches the level of plus-energy building when using CO_2 factors and is near the ZEB balance using PEFs. In the reality it has a weighted load similar to the boiler, but as CHPs are also able to generate electrical energy in their operation, it gives a greater amount of weighted generation. CHP+ST is therefore considered the best heating system before adopting economical parameters. The worst is undoubtedly El-Boiler+ST, which is not a very efficient system due to high electrical consumption, all added to high electrical weighting factors.

Energy mismatch of every system can be easily studied looking into the electricity month chart graph. Normally there is a good match between the electrical demand of office buildings (occupancy during the day, cooling peaks in summer) and generation from PV. The problem arises in cold climates like Norway, where the heating energy demand hugely increases in winter days, while the generation is practically nil due to the few hours of solar radiation. This phenomenon appears in building systems that only generate electricity using PVs. If the building uses other systems of electrical production that can also generate during winter days, instead of only PV, it will be easier to match the load. The best example is the CHP, as it can be seen in the table beside the electricity month chart the load match is 91%. A higher match also gives higher self-consumption, because the heating and cooling system consumes and the generation system produces at the same time. This could also be appreciated if CO_2-eq emission balances for CHP and Bio Boiler were compared. Although both have the same weighted load in the load/generation balance (red line), when self-consumption is subtracted to get imported/exported balances (green and blue line) CHP shows a significantly lower load, especially when measuring monthly values.

It should be mentioned that there is a possible error in the ASHP energy demand because IDA-ICE results do not directly include the cooling consumption of the additional chiller, it has been added separately. The cooling mode of the reversible air-to-water heat pump was not enough to cover the whole cooling demand, so this additional chiller of 18 kW is in charge of covering the remaining energy. As was explained in chapter 3, a generic chiller is used to imitate the performance of the heat pump working in cooling mode. Since it is not possible to include two chillers in the same IDA-ICE model, both consumptions have to be individually calculated and then the additional chiller power should be added when the reversible heat pump fails to satisfy the cooling demand.

4.3 Cost optimal analysis

For cost analysis calculations each building energy system is going to include costs for the base heating system, cooling system and generation system. Two different calculations, with and without solar thermal collectors, are performed for those technologies that are preferable to install together with certain amount of solar thermal collectors, according to the ST optimization. Cost of peak load heating systems, 30 kW electrical boilers in this case, are normally excluded from cost analysis in this kind of studies. This is basically because they have a very low investment cost compared with other technologies and they are needed by every system. The final goal of the project is to perform a global cost comparison between energy supplies, thus a system used by all of them can be perfectly discarded without compromising the results. In fact, the same argumentation can be applied for PVs, since the same area is used in all cases. However it has been opted for including PV costs because they are an important part of total investment costs, therefore representing a more realistic monetary calculation.

Heading system	Cooling system	Generation system
District heating + 7 m^2 ST	30 kW chiller	346 m^2 PV panels in the roof
CHP + 5 m^2 ST		
Bio Boiler		
El Boiler + 13 m^2 ST		
Ground source heat pump	3x120m boreholes	
Air source heat pump	Heat pump in cooling mode + 18kW chiller	

Table 4.2: Systems included in cost-optimal calculations

Global cost calculations are collected in an Excel file that automatically makes the comparison between systems by plotting the results in different columns. Each system has its own column divided in three colours, as it is illustrated in figure 4.1. One simply needs to briefly look the graphs below to realize that the ground source heat pump is the cost optimal system for the concept building. GSHP not only has a low investment cost due to the absence of cooling chiller, but it also has a low energy consumption that results in low energy costs. This could have been foreseen because it is known that free cooling with ground boreholes reduce both investment costs and energy costs. Besides, high energy and maintenance costs make district heating with and without ST the most expensive technology among possible options.

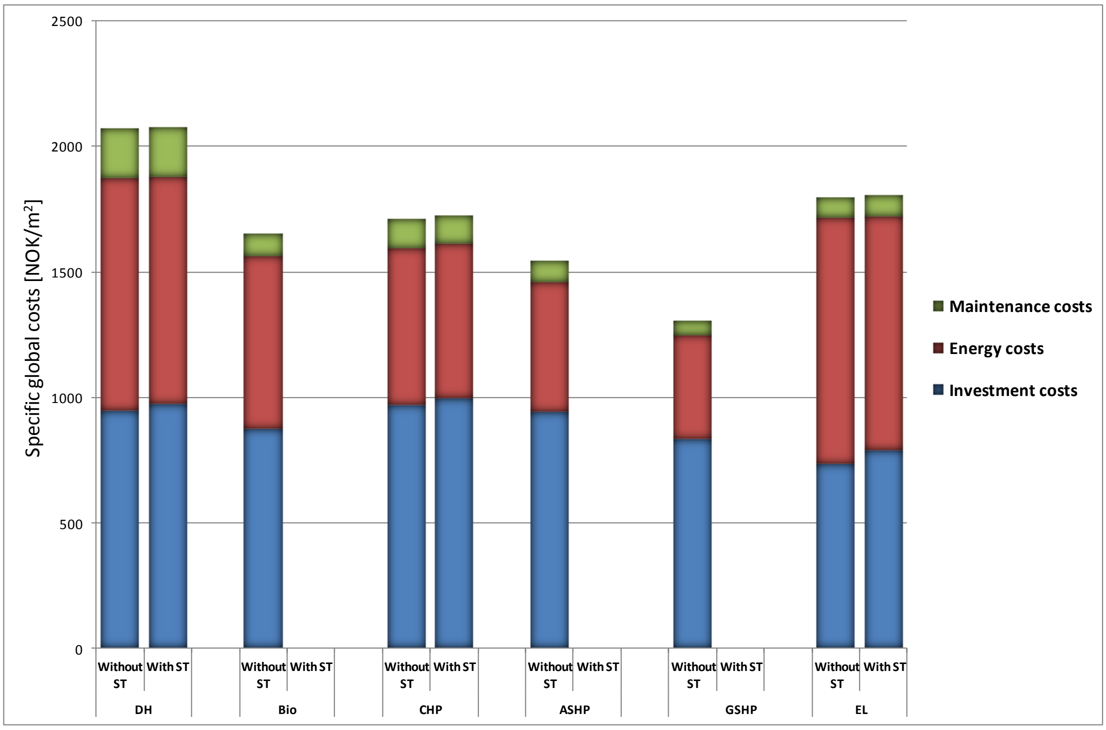


Figure 4.1: Cost analysis results, financial perspective

Aside from the financial calculation, cost optimal results can also be calculated in a macroeconomic perspective. As explained in the theory, in a macroeconomic perspective all the prices should be taken into account excluding all applicable taxes, VAT, charges and subsides. Apart from the three cost categories already included in the financial perspective, the cost of greenhouse gas emissions are also added to global costs calculation. The discount rate, inflation rate and the various price escalation rates are the same as in the financial analysis.

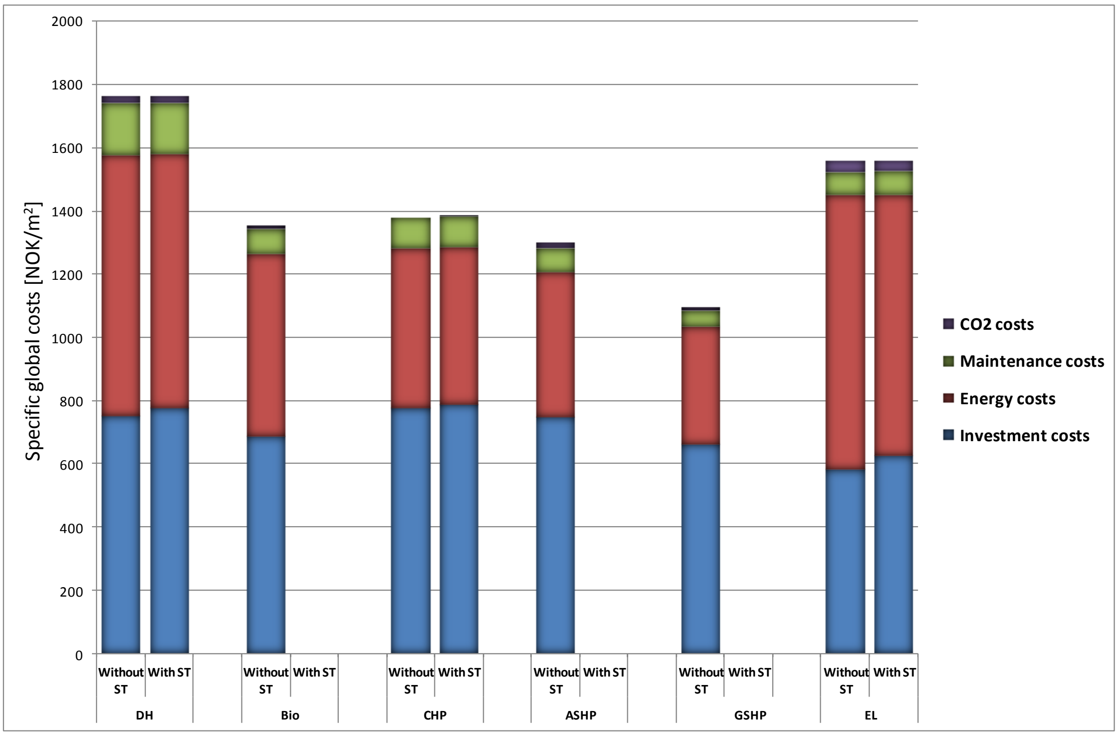


Figure 4.2: Cost analysis results, macroeconomic perspective

As figure 4.2 shows results are practically the same as in the financial calculation, but with lower global costs. GSHP is still the cost optimal system and the other systems do not change in order of preference. After giving an overview of values that have been adjusted to calculate these new results, some answers can be given to the question of why results do not change. The first value that should be modified in a macroeconomic calculation is the value added tax (VAT). This tax of 25% is applied to every cost used in the analysis, like investment costs, energy costs and maintenance costs. For this reason, there is not big change in any system over the others, because every technology has to remove that 25% of all expenditures. Thus, results are only rescaled to lower global costs but in more or less the same proportion. In addition, other taxes like for example the electricity certificate applied in the electricity price are not large enough to change the difference between energy carrier prices, so results will remain the same. And so with subsidies that are given to finance some energy supplies. Moreover, CO_2 emission costs are not big enough comparing with other cost categories to change the results in any significant way. Therefore, only financial calculations will be taken into account to later showed results.

4.4 Cost-emissions and cost-energy graphs

The most suitable energy supply system in an early design phase analysis should be finally decided using a graph like the ones presented in this section. In this diagram x-axis gives the balance for CO_2 emissions or primary energy, while y-axis gives global cost. Each column represents a different energy supply technology, and they are ordered according to specific CO_2 emissions (kg CO_2/m2) given by the balance, from the lowest to the largest CO_2 emitter. One should get a glimpse of both graphs beforehand to make a final decision of the best system for the office building.

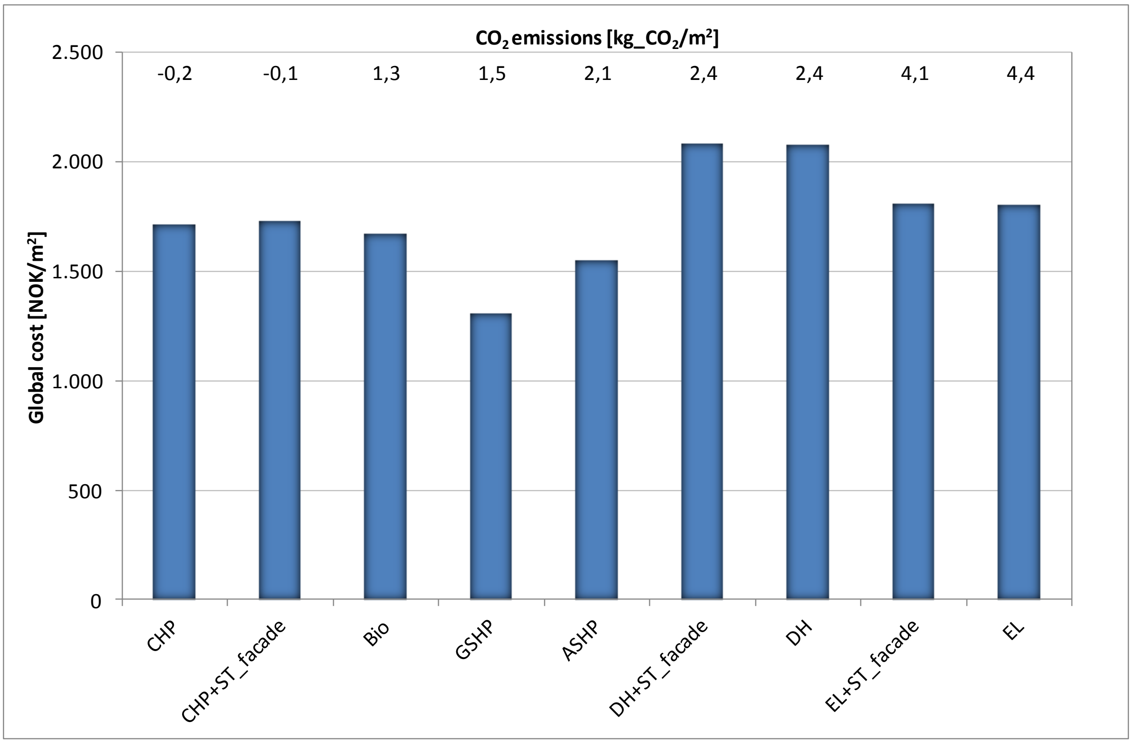


Figure 4.3: Cost-emissions graph

Results for both weighting factors the CO_2 emissions and primary energy are presented in this section. However, as mentioned in the current NZEB definition, Norwegian studies should be primarily focused on CO_2-eq emissions until primary energy factors are developed. Also by comparing figures 2.3 and 2.4, it can be seen that both factors show below the figure, almost the same order of preference of technologies; there is only a change with the ASHP. This actually means that the weighting factors used in this project respect more or less a proportional difference between energy carriers, so final results will be mostly the same for both of them. In this case CHP is the system positioned farthest to the left, the one with less CO_2 emissions. Thanks to its electrical generation during winter days, CHP will compensate the building's energy demand in a way that it reaches the level of plus energy building. This is the same as saying that the building has higher weighted energy generation than weighted demand, for that reason it gives a negative value in the balance. If solar thermal collectors are installed together with the CHP system, power generation will slightly decrease and likewise specific global costs will decrease. When the difference in CO_2 emissions is not very high, normally the most reasonable is to install a cheap system rather than an efficient one. There could be for example a discussion between installing a GSHP, the cost optimal system with a great difference in expenses over other options, or a CHP instead, the best positioned in the NZEB balance. This decision will depend on whether the money is the most important factor in the study or not. In other studies like in "Implementing the cost-optimal methodology in EU countries" [15] developed by BPIE, two limits are set to decide the most cost-effective option towards the NZEB definition. A horizontal line defines the cost optimal limit, so every system below will be considered as cost optimal, and a vertical line defines the limit for primary energy consumption, so the chosen system shall consume lower primary energy than the permitted limit. That will be the most reasonable way to choose the best system for the building.

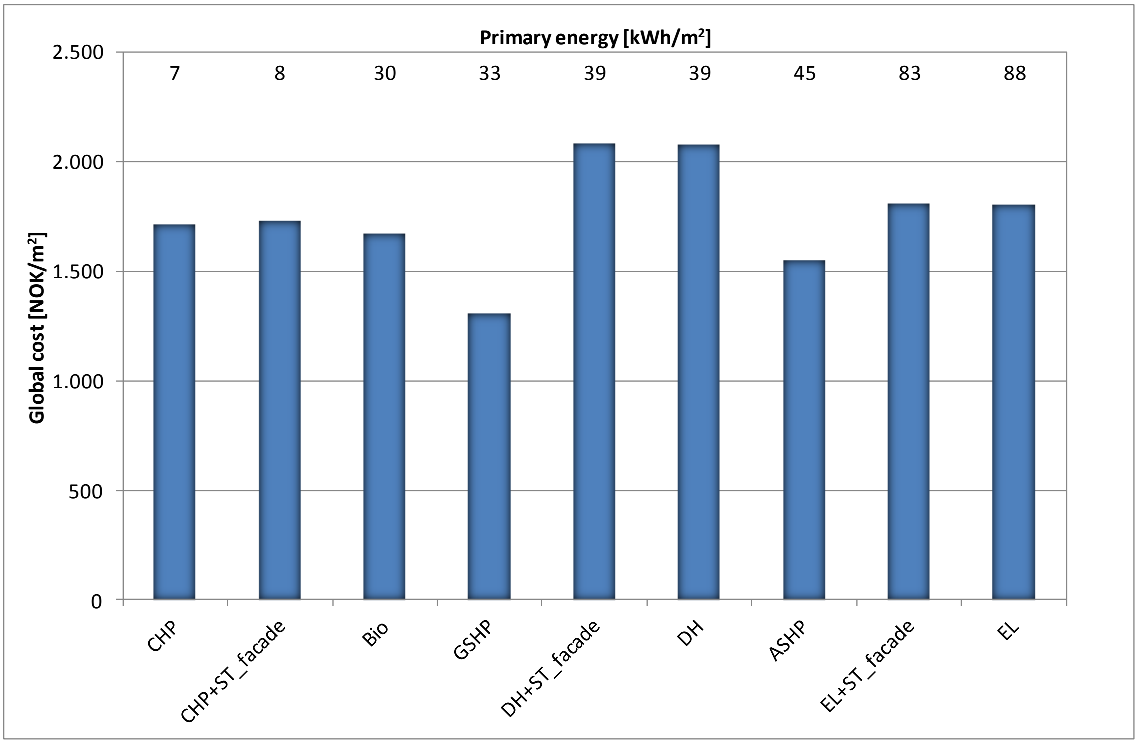


Figure 4.4: Cost-energy graph

5. Sensitivity Analysis

So what if some variables of the analysis are changed? This is the question that one should ask before performing a sensitivity analysis. A sensitivity analysis is mainly used to determine how sensitive a model is to changes in the value of model parameters. Thereby new simulations will be carried out after changing two variables that are directly related with final parameters, namely the analysis will observe the change in CO_2 emissions and global costs when other parameters are changed. This analysis therefore helps to contrast the results by studying the uncertainties that are normally associated with some model parameters. These variables are usually uncertain values, so during the modelling other possible scenarios could have been chosen; this section studies those possible scenarios.

5.1 Price escalation

Energy price development or escalation has been considered as an important uncertainty when defining the economic parameters. This percentage value represents how the energy price changes over the years. It should be remembered that a cost-optimal analysis is a thirty-year study, so it seems difficult to estimate exactly how the energy price of a country will change over so long period of time. Following a document developed by the Building Performance Institute of Europe (BPIE), previously mentioned in this project, about the cost-optimal methodology applied in different countries [15], three different scenarios have been considered. A first basic scenario or reference scenario is a 2.8 %/year increase in the energy price, the one that has already been studied in chapter 4, and two further scenarios with a 1.5% increase and decrease over the initial scenario.

5.1.1 ST optimization, energy price developments

First of all, one should realize where the parameter that wants to be varied is an input. In this case the price escalation is an input in the ST optimization as well as in global costs calculation. Table 5.1 shows how the optimal ST area, total savings and solar fraction change for both scenarios compared with the basic scenario. It can be remarked that a lower or higher energy price development does not change the initial substitution price, but it changes the price that will be paid for the energy in later years. If the energy price increases in a lower rate over the years, at the end of the lifetime energy costs for the base heating system will be lower. This means that it is more difficult to obtain costs savings when solar thermal collectors are installed. Like the table below shows, a low energy price development of 1.3%/year leads to lower optimal ST area in every system, thus solar thermal installation is no longer profitable with most systems. Even if solar energy is free, the price of other energy carriers is so low during the calculation period that total energy savings do not compensate the investment of the ST system. And the opposite happens when a high energy price development of 4.3 %/year is applied, more solar thermal collectors are required. Total savings and solar fraction change proportionally to the optimal ST area. Consequently more simulations have been performed with new optimal ST areas in order to perform new cost analysis for each scenario.

Price escalation 0.013	**Substitution price [NOK/kWh]**	**Optimal ST area $[m^2]$**	**Total Savings [NOK]**	**Solar fraction**
District heating (DH)	0,77	0	0	0
Air source heat pump (ASHP)	0,32	0	0	0
Ground source heat pump (GSHP)	0,24	0	0	0
Combined heat and power (CHP)	0,75	0	0	0
Biomass boiler (BB)	0,5	0	0	0
Electric boiler (EB)	0,87	4	327	0,03

Price escalation 0.043	**Substitution price [NOK/kWh]**	**Optimal ST area $[m^2]$**	**Total Savings [NOK]**	**Solar fraction**
District heating (DH)	0.77	16	13600	0,11
Air source heat pump (ASHP)	0.32	0	0	0
Ground source heat pump (GSHP)	0.24	0	0	0
Combined heat and power (CHP)	0.75	14	9904	0,10
Biomass boiler (BB)	0.5	0	0	0
Electric boiler (EB)	0.87	23	27954	0,15

Table 5.1: ST optimization results for new price escalations

5.1.2 Cost-emissions, energy price developments

Cost optimal results for low and high energy price development scenarios are shown in the next page, figures 5.1 and 5.2. Apparently the cost-optimal option does not change compared to the basic scenario in any variation. Results only show rescaled global costs and different CO_2-eq emissions for those systems with solar thermal collectors. Focusing in this second effect, it seems normal to find new CO_2 emissions when the area of ST changes. In a low scenario district heating and CHP systems with ST directly disappear from the analysis, while the El-Boiler+ST system gives higher CO_2 emissions. On the other hand, a high scenario results in systems with lower CO_2 emissions. It can be concluded that a bigger solar thermal area covering a bigger part of the heating demand leads to lower CO_2 emissions. This is because solar thermal collectors are greenhouse emission free systems; they collect energy from the sun without any harmful effect on the environment.

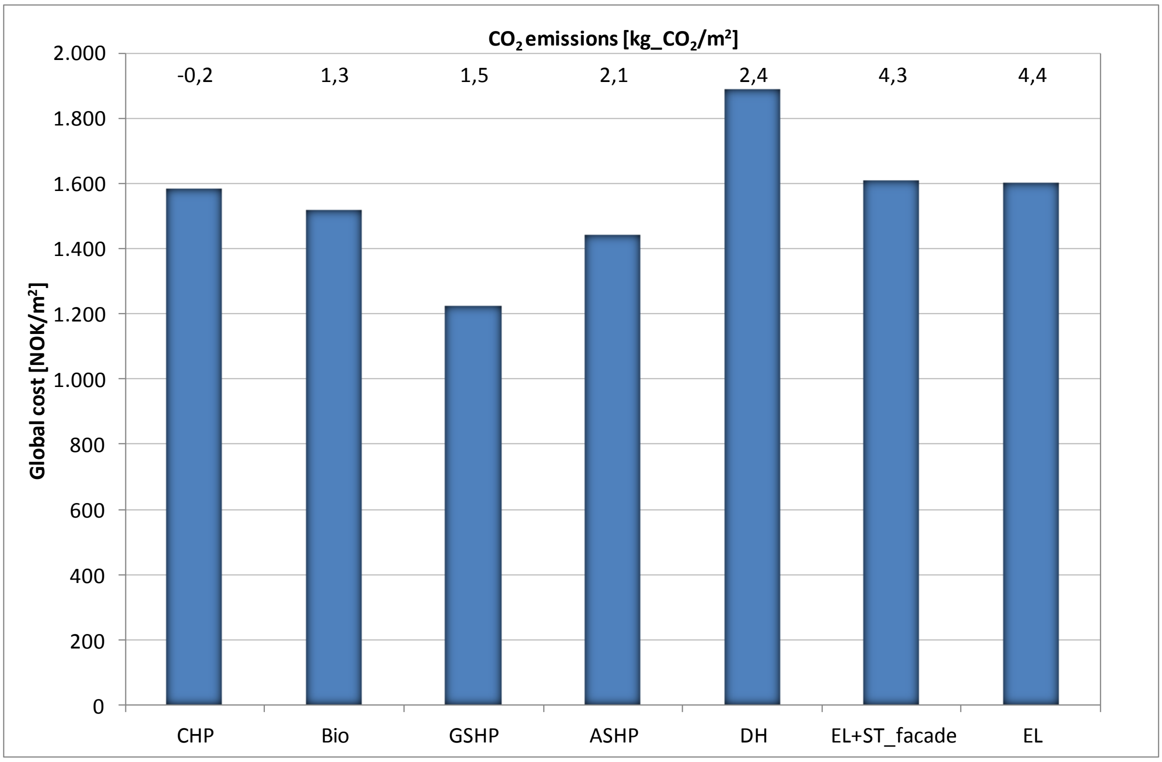


Figure 5.1: Cost-emissions graph, low energy price development (0.013)

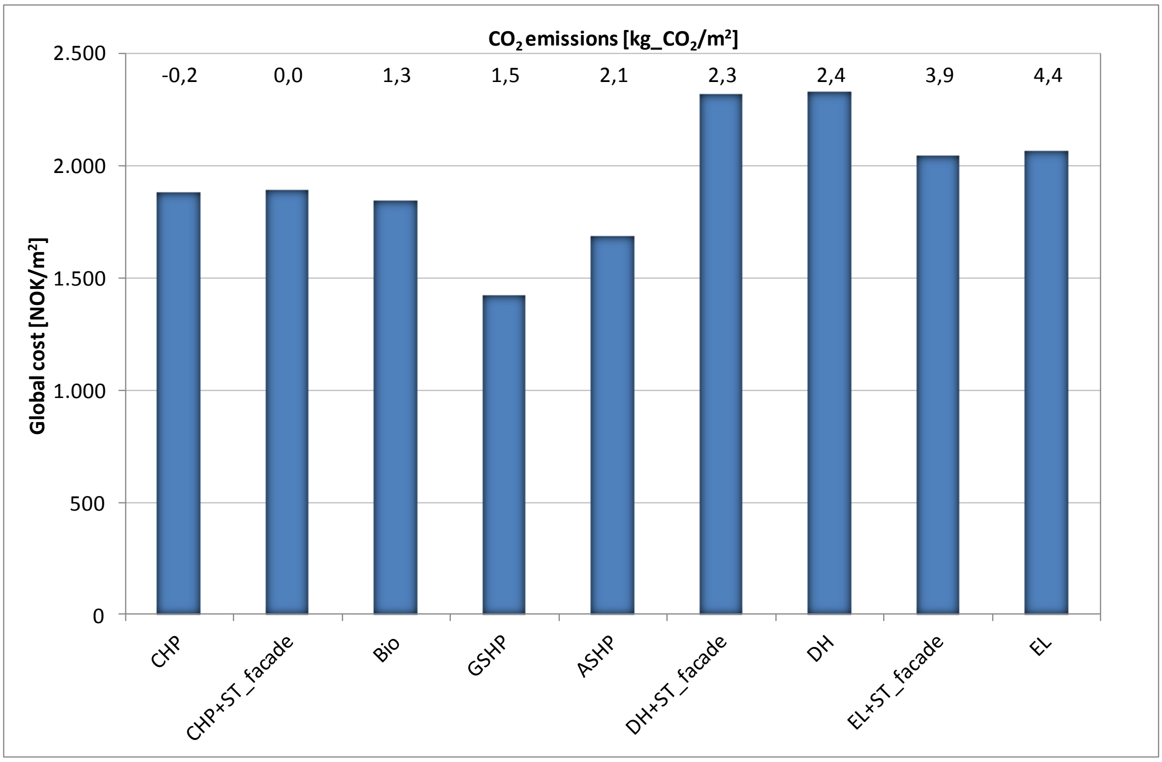


Figure 5.2: Cost-emissions graph, high energy price development (0.043)

In addition, global costs are rescaled in a different extent depending on the energy consumption of the base heating system. Results show lower global costs when the energy price development is reduced in a 1.5% and higher global costs when it is increased in the same amount. This is an obvious effect due to the proportional variation of energy costs with the price escalation. Aiming to show a real sensitivity analysis a diagram has been created. It shows the percentage change in global costs in the x-axis, separated in the y-axis by each energy supply system. This diagram provides such a way by clearly identifying those systems whose uncertainty drives the largest impact in global costs. The middle line represents the basic scenario; red columns give the percentage value of how global costs change in respect to the basic scenario when a low energy price development is applied and green columns give the same value but with a high development scenario. This graph is an easy way to visualize the proportional relation between global costs and price escalation.

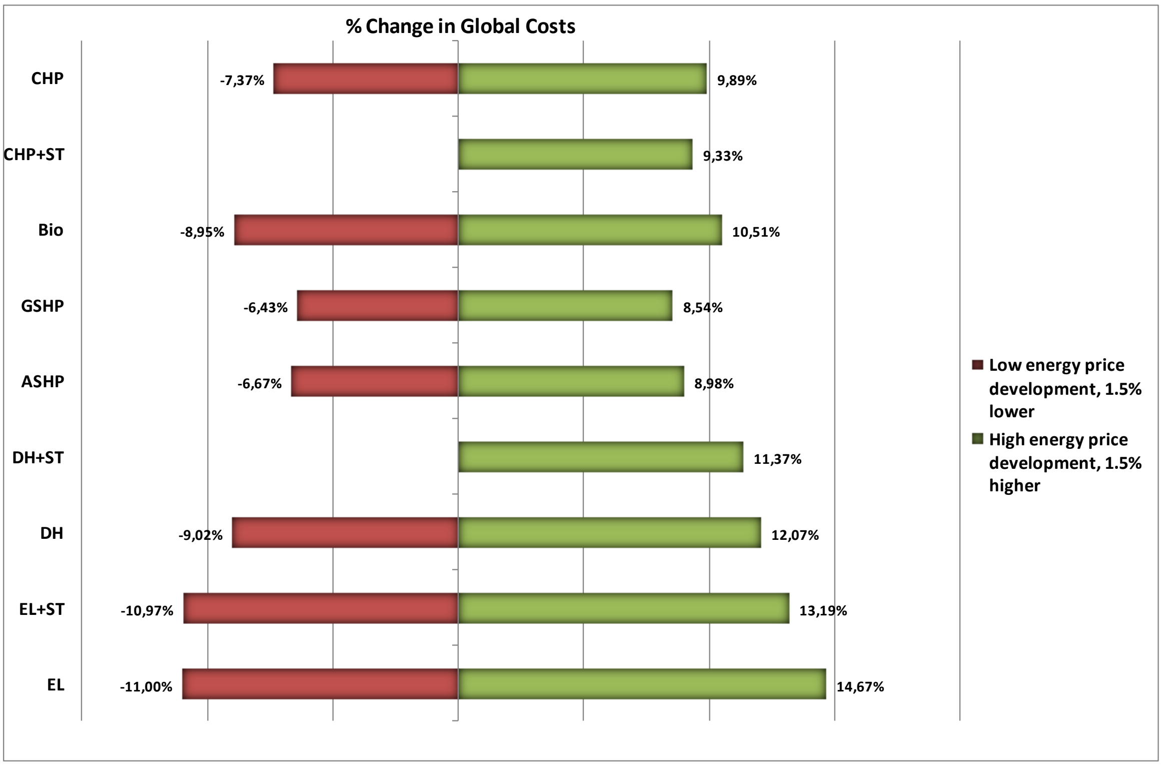


Figure 5.3: Sensitivity analysis for energy price development

Due to the current high price for electricity and the high energy consumption of the electric boiler, the effect of a different energy price development is more obvious for that system than for others. Energy supplies with lower energy consumption, like heat pumps, show smaller variations. Even if the variation is the same for both sides, it should be highlighted that systems are not affected in the same way. Global costs are proportionally higher when the energy price development increases, i.e. bigger green columns than reds in the graph. This is basically a mathematical effect.

5.2 Additional PV in the west façade

The second parameter regarded as an uncertainty is the amount of PV installed in the building. It has been considered like an interesting variation because at first sight a different PV area appears to change both CO_2 emissions and global costs. Since the entire roof is already covered by PV another part of the building has to be found to install more panels. The south façade, the second best option is also used for solar thermal collectors with some energy supplies, so the additional PV system is going to be placed in the west façade. The energy production will be lower comparing with the west-east roof installation, making necessary to add a big new area of PVs to see an appreciable change in results. 100 m2 of PVs are therefore installed for the sensitivity analysis, covering almost all the available west façade.

In this case the optimal ST area remains the same, because the amount of PVs does not affect in any way how to dimension the heating system. Besides, in this sensitivity analysis it neither changes the cost optimal energy supply system, as it can be seen in the image below.

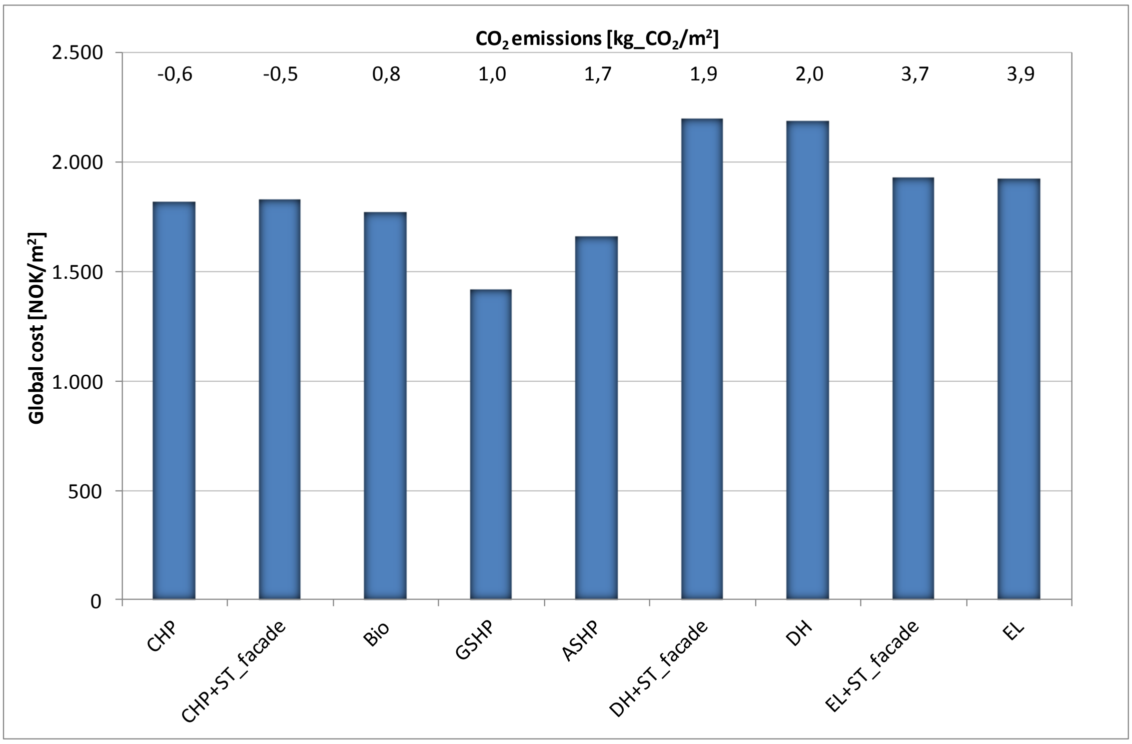


Figure 5.4: Cost-emissions graph for 100 m^2 more of PVs in the west façade

Higher global costs and lower CO_2-eq emissions are according these results the effects of installing more photovoltaic panels. More PVs tend to raise the total investment cost, while the extra generation that they provide compensates even more the weighted imported energy to the building. To understand easily both effects two percentage graphs are presented in the next page illustrating in which extent global costs and CO_2 emissions change with the variation. The first image shows that precisely GSHP, the cost optimal system, is the one that experience a larger impact in global costs. This is simply because GSHP has less global costs, so more PVs means proportionally a greater investment comparing with other systems. In the second graph both CHP systems also show different variations due to their smaller weighted demand and bigger weighted generation with regard to other technologies. These differences are only a matter of proportion, but both graphs only attempt to give a simple overview of the effect that variations have.

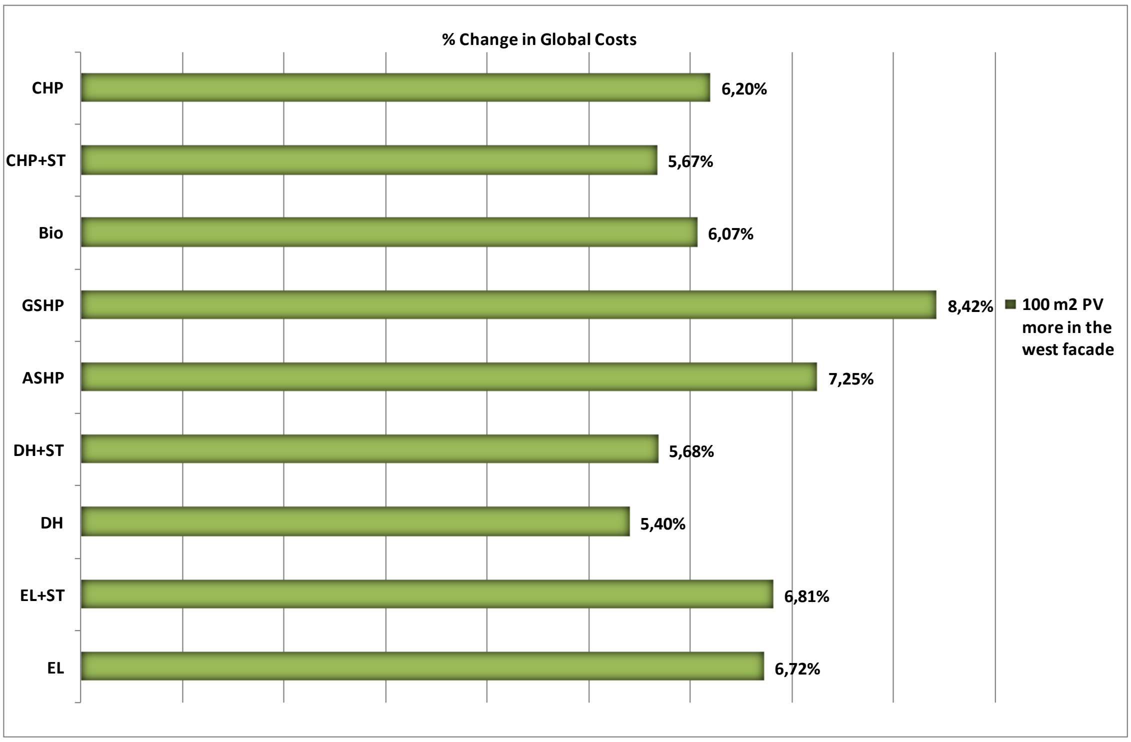


Figure 5.5: Sensitivity analysis for amount of PV installed, change in Global Costs

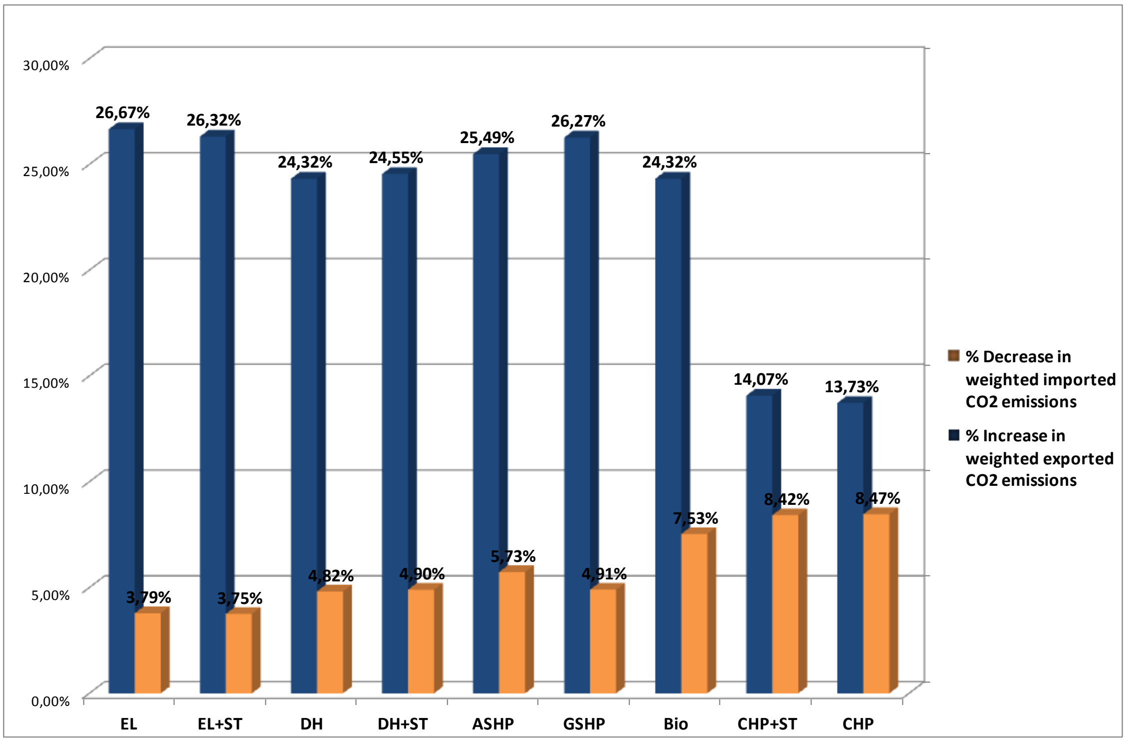


Figure 5.6: Sensitivity analysis for amount of PV installed, change in CO2-eq emissions

6. Discussion

This section aims to give a review throughout the project, highlighting the most remarkable points and trying to discuss the uncertainties that appear during the study. In this kind of analysis, where a countless number of parameters take part, it may appear different types of simplifications and questions regarding the followed process to obtain the results. Definitely, this is a discussion about the early design methodology for zero emission buildings in terms of accuracy and meaning.

The final goal of this Master Thesis, as a project proposed by the ZEB centre, is to show the necessary knowledge that is needed to apply the cost optimal methodology in any Norwegian office building. A previous study has only been focused on residential buildings, while this new analysis extends the scope to buildings that need a better control of indoor climate. Office buildings introduce the cooling demand into the cost-optimal methodology, giving special attention not only to parameters that control indoor conditions but also including new energy supply systems that have to be capable of providing the necessary additional energy. This kind of buildings appears to represent a greater interest for constructor companies and consultants involved in low energy building projects. The current cost-optimal methodology for early design phase is a set of guidelines that should be followed in the process of selecting the best energy supply, and it is comprised of a number of excel files necessary to make calculations that have not been developed yet by any simulation program. This is a really useful calculation method to compare different options and choose the most appropriate one from an economic and efficiency point of view. It is also important to mention that most of the information and files used during the project are part of a cost-optimal guideline that is still unpublished. Indeed, this means that data source of this project has been in a continuous development, so it could happen that some data or methods become obsolete during the reading of the project.

6.1 Results

Results showed in Chapter 4 are a practical application of the cost-optimal methodology to an office building model which was previously used by the ZEB centre for a zero emission analysis. This building represents how an office modelled with the passive house standards should be. The same analysis can also be adapted to other low energy demand office buildings in real studies. For the calculation example six different base heating systems have been selected, actually the most indicated ones for a Norwegian study. Final results are presented in a two axis graph where every energy supply alternative is positioned in terms of specific global costs and net CO_2-eq emissions.

According to global costs in a basic scenario of energy price development, the cost-optimal system is composed of a ground source heat pump (GSHP) together with an electric topup heater to satisfy the heating demand, a chiller for the cooling demand and a PV system in the roof for electrical generation. There is a big difference between the GSHP and other possible options on the basis of global cost results. It could be explained by several arguments as follows. To begin with, the ground source heat pump is the only system which does not need a chiller for the cooling period, because its installation brings some boreholes that provide free cooling to the system. In accordance with collected economic data from manufacturer companies, it can be drawn that boreholes resulted in lower expenses than chillers, what evidently causes a lower investment and energy costs in the final budget.

An analysis in early design phase does not seek for exact cost values in calculations, but they should be enough reliable to obtain accurate results. Energy costs are very low for the GSHP, apart from the fact that the energy consumed by the chiller is removed, also because heat pumps are usually efficient systems with low energy consumption. Even though, they consume electricity which is the most expensive energy carrier per kWh. Investment and maintenance costs for each energy supply technology will depend on both the country where the study is performed and the selected company as cost data source. Furthermore, the installation of boreholes is also a sensitive input due to the cost difference in terms of the location of the system. Anyway, costs of this project are basically an approximation given by a manufacturer.

Besides, the net ZEB balance based on CO_2 emissions gives as a result the combined heat and power (CHP) system as the alternative with the best energy performance. In point of fact, the building performance has a negative value, since the weighted exported energy to the grid is larger than the imported one. The additional power generation and the use of pellets as energy carrier for heating generation are the responsible for such a good result. CHP with and without ST is positioned above the ZEB balance line, turning the building into a plus-energy building. Nevertheless, a building above the balance does not necessarily mean low energy consumption. Indeed, a CHP system has a great amount of fuel energy imported that finally increases energy costs, even if imported electricity is totally compensated with exported electric energy. This is the main reason that the CHP system shows higher global costs than the biomass boiler or heat pumps.

The sensitivity analysis in chapter 5 studied the impact in final results when the energy price development and the amount of PVs vary. Any particular variation has been found when carrying out changes in the values, neither in the cost-optimal selection nor in the CO_2 emission balance. Only simple relations can be deducted from the sensitivity analysis. A high energy price development means that the net present value of future energy costs increase compared to the basic scenario, what leads to higher total global costs. In addition, there is a need for a bigger area of solar thermal collectors, dropping primary energy and CO_2 emissions values. Otherwise, a low energy price development achieves exactly the opposite effect. Apart from that, the installation of more PVs in the west façade increases investment costs, while the building's energy performance improves significantly. This is mainly due to a reduction of imported electric energy and an increment of exported energy to the grid.

In the authors opinion a GSHP system will be the most convenient alternative for the concept building thanks to its low global costs and reasonable low CO_2 emissions. However, as it was mentioned in the results section, the best possible scenario would have been to have had defined two limits for global costs and CO_2 emissions, and then take a decision according to systems that meet the requirements from both sides. Actually the 5th article of the EPBD recast require member states to establish different categories of reference buildings that are representative of their functionality and climate conditions. Norway should define a reference office building with limits for CO_2 emissions and a cost-optimal level so the most cost-effective system can be chosen with both values as a benchmark.

6.2 Possible uncertainties

Weighting factors can be considered as important parameters when obtaining final results. They are multiplied by imported and exported energy to the building, giving more weight to some energy carriers over the others. A little variation in their value could drastically change the energy performance of the building. Despite the importance of these factors in energy performance calculations, it seems that there is not any agreement about their final magnitude. In the Norwegian case, there are no official factors yet, so in this case they have been collected from a previous study. For example, it is used the average European electricity factor, although Norway is one of the countries with the cheapest and cleanest electricity production in Europe. Consequently, some values might be lower while others could be higher. Even so, with the current available information those applied in the project seem to be the most appropriate ones.

Energy cost is completely based on building consumption, size of the building, current rates and price predictions, thus it is directly linked to the result of energy performance calculation. Considering that simulations give the necessary values for energy cost calculations, it is of vital importance to use a program that can be relied on. Accordingly, IDA-ICE has been proved as a reliable tool when calculating energy performance and energy consumption of a building. Once the building model has been completely defined, the program gives a number of useful output graphs and tables for this kind of calculations. Standards, research publications and theory are used to set the building envelope and technical installation parameters, but sometimes the work is not as simple as collecting data. As explained in chapter 3.2.2, during the setting of technical installations, several trial and error processes have been carried out in order to try to avoid high peak loads as well as search for desirable indoor conditions. Each building will behave in a different way, so this is a necessary and long step when seeking to model a building with a real performance and low energy consumption.

Although the program calculates accurately the results, IDA-ICE also presents a lot of simplifications to ease the work of the user. With the IDA-ESBO layout, only the most important parameters are considered for simulations. The biggest problem has been found when defining the cooling mode of heat pumps due to the impossibility of defining a realistic reversible one; neither through a reversible model nor through an air source chiller simulating the cooling mode. It has been tried to imitate the cooling operation in the best possible way, using a generic chiller adjusted with the seasonal performance factor and the evaporator capacity. Results might not be exactly the same, but up to a point it should be enough for an early design phase with the available tools.

Apart from that, in the author’s opinion, IDA-ICE especially gives a simplified view of the PV system. The program dismissed among other things the separation and self-shading between panels. Partial shading of the modules could be a cause of mismatch between the energy generated by two or more modules, which is one of the major sources of losses in a photovoltaic system. Modules are connected in series, and that electrical mismatch in the output might decrease the electrical production of the PV array. Electrical mismatch could also occur due to shading by the surrounding buildings, trees, or other obstacles that interfere with the direct sunlight striking the solar array; although these are normally neglected in early design phase calculations. In conclusion, it seems that IDA-ICE needs to improve the PV model or maybe the generated electricity could be calculated with accompanying software.

7. Conclusions

To sum up, the preliminarily conclusions for this study are:

1) When obtaining satisfactory indoor conditions, the concept office presents a high and steep peak load for heating the building in winter, while the cooling demand stands for half of the power in summer. Such a large heating peak, the power curve should be divided in base and peak loads. An electric boiler with low investment cost covers the peak produced in high demand periods and a low operation cost system covers the base load produced along the year. Instead, the cooling demand can be satisfy in different ways, among others, a reversible air source heat pump working in cooling mode, boreholes implemented with a ground source heat pump and a normal cooling chiller. All of them will be dimensioned covering the maximum cooling power which occurs in the warmest day with solar radiation. If the evaporator of the reversible heat pump has not enough capacity to fill the demand, an additional chiller should be installed to cover the rest of the power.

2) The ST optimization results in low solar collector areas required for every heating system. Most of them present a low substitution price due to both low energy consumptions or prices. Those systems that have an optimal area of solar collectors present similar global costs with and without ST, mainly because higher investment costs are compensated with lower energy costs.

3) A ground source heat pump, which obtains free-cooling through boreholes, is the optimal system for a normal office building of 1980 m^2. It gives the lowest global costs with quite low value of CO_2 emissions. One of the reasons is the ability of its borehole system to satisfy the entire cooling demand without the need of an additional chiller. When covering the entire roof with PVs, the office can be labelled as a nearly energy building, since it does not meet the NZEB balance.

4) A combined heat and power system will be the only one able to overcome the NZEB balance line, achieving a label of plus-energy building. The power generation provided by the CHP together with the PV generation is enough to ensure higher values of exported energy compared to the imported one.

5) Variations in the energy price development estimation do not change the results significantly. They only rescale global costs in higher values for a high development scenario and the opposite for a low development scenario.

6) Every system but the CHP, is far from meeting the NZEB balance, even if more PVs are installed in the west façade. This option will normally increase investment costs without either obtaining significant improvements.

8. Future work

Development of new analysis for office buildings is of great interest to companies working with zero emission buildings. International reports show that large companies are the most interested in developing energy efficient offices for their own headquarters. As any other product, methods like the one developed in this Master Thesis have to be commercialized and need to be oriented towards a market target. For that reason, new projects focused on real cases seem to be necessary, thus companies can also give their own feedback about their real needs. The correction of calculation errors and the implementation of new models are important steps within this context. It can be said that somehow the methodology for the selection of energy supply system in early design phase is as well in an early design stage.

First and foremost, Equa, IDA-ICE simulation software's developer, should introduce new energy system models in their templates. Reversible heat pumps or at least air-source chillers are needed for a more realistic study of buildings with cooling demand. Simplifications using generic chillers models, where only two parameters can be set, do not seem sufficiently reliable. Apart from that, the company should also consider the possibility of implementing the Excel files used in the methodology in its own system. It should be reminded that most of the input data for the methodology is directly copied from IDA-ICE result files. An automatic calculation of the cost-optimal methodology will ease the work of the user, so much that anyone with a minimum knowledge could do it.

Regarding the definition of technical installations in further studies, currently used efficient systems could be introduced. Nowadays low temperature heating and high temperature cooling systems are in the forefront of efficiency due to low losses in the distribution. For instance, chilled surfaces with ceiling panels, where higher temperatures are needed, could be a good way to reduce even more the energy consumption for cooling purposes. The same happens with indoor heating; new systems can further reduced the distribution temperature, thus replacing hydronic radiators by other water systems. In this way, lower energy demands will be achieved that would simplify the fulfilment of the NZEB balance. Research studies should be adapted to current times, trying to implement new findings in any area.

At last, it seems like the concept of Smart City is gaining momentum among researchers. European legislations are at the same time investing in NZEBs for both new constructions and refurbishments as a way of facing environmental challenges. Future Smart Cities will need to care about the interaction between the NZEB building and the grid, so new Smart Grids could be designed with minimum losses. So to a certain extent, new analysis should have an insight view into the mismatch concept.

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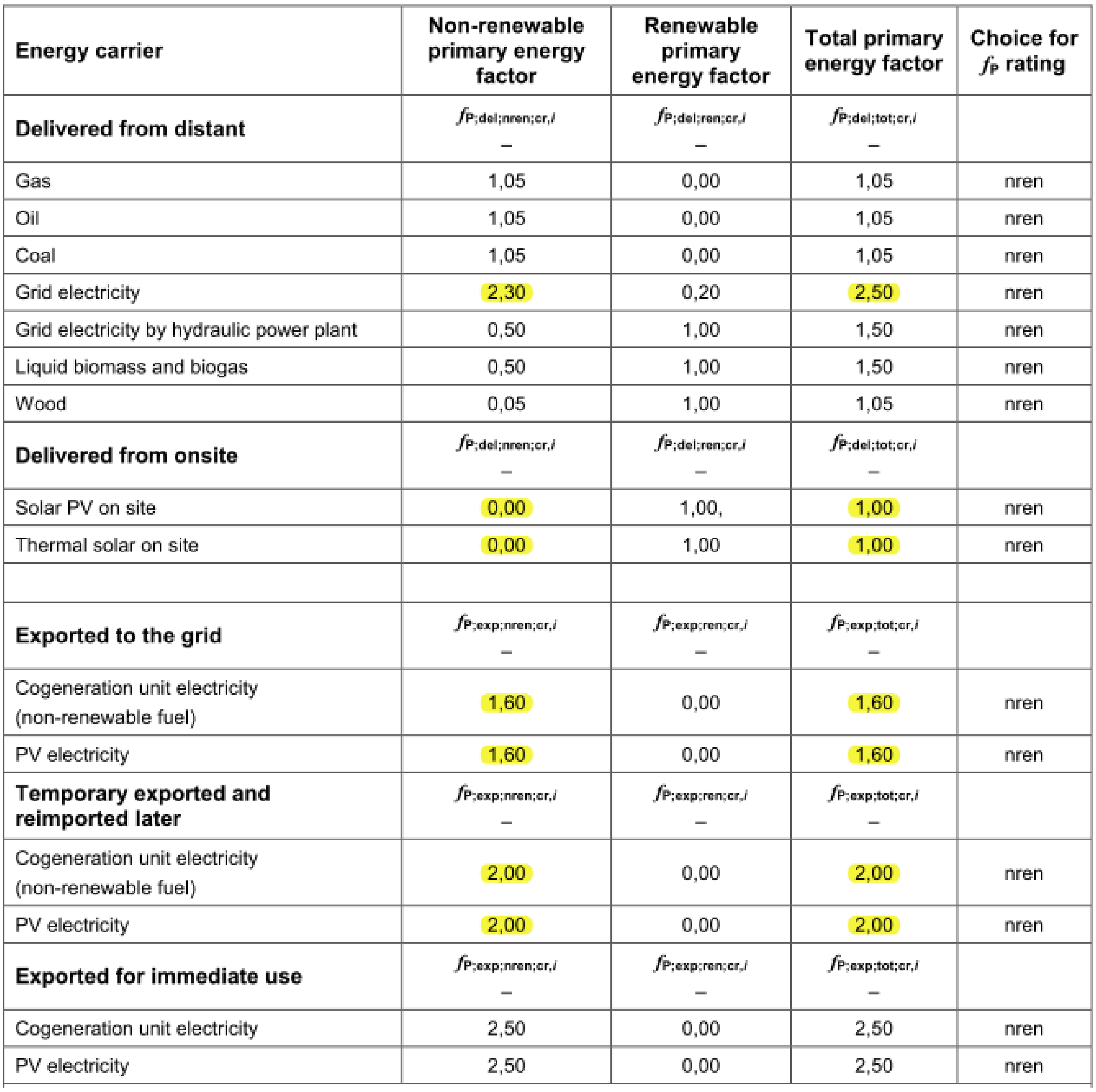
Appendix A

Table 0.1: Primary energy factors, obtained from prEN 15603

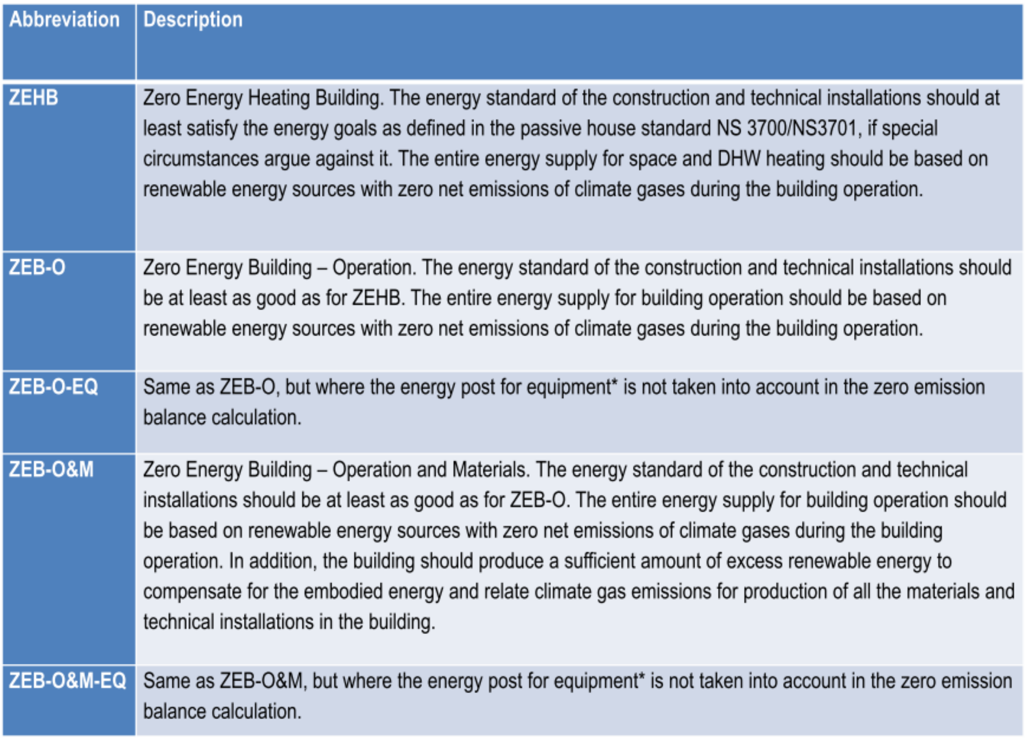


Energy carrier	**Non-renewable primary energy factor**	**Renewable primary energy factor**	**Total primary energy factor**	**Choice for f_P rating**
Delivered from distant	$f_{P;del;nren;cr,i}$ –	$f_{P;del;ren;cr,i}$ –	$f_{P;del;tot;cr,i}$ –	
Gas	1,05	0,00	1,05	nren
Oil	1,05	0,00	1,05	nren
Coal	1,05	0,00	1,05	nren
Grid electricity	2,30	0,20	2,50	nren
Grid electricity by hydraulic power plant	0,50	1,00	1,50	nren
Liquid biomass and biogas	0,50	1,00	1,50	nren
Wood	0,05	1,00	1,05	nren
Delivered from onsite	$f_{P;del;nren;cr,i}$ –	$f_{P;del;ren;cr,i}$ –	$f_{P;del;tot;cr,i}$ –	
Solar PV on site	0,00	1,00,	1,00	nren
Thermal solar on site	0,00	1,00	1,00	nren
Exported to the grid	$f_{P;exp;nren;cr,i}$ –	$f_{P;exp;ren;cr,i}$ –	$f_{P;exp;tot;cr,i}$ –	
Cogeneration unit electricity (non-renewable fuel)	1,60	0,00	1,60	nren
PV electricity	1,60	0,00	1,60	nren
Temporary exported and reimported later	$f_{P;exp;nren;cr,i}$ –	$f_{P;exp;ren;cr,i}$ –	$f_{P;exp;tot;cr,i}$ –	
Cogeneration unit electricity (non-renewable fuel)	2,00	0,00	2,00	nren
PV electricity	2,00	0,00	2,00	nren
Exported for immediate use	$f_{P;exp;nren;cr,i}$ –	$f_{P;exp;ren;cr,i}$ –	$f_{P;exp;tot;cr,i}$ –	
Cogeneration unit electricity	2,50	0,00	2,50	nren
PV electricity	2,50	0,00	2,50	nren

Appendix B

Ambition levels

Figure 0.1: Different ambition levels for ZEBs, obtained from the ZEB centre's web page



Abbreviation	Description
ZEHB	Zero Energy Heating Building. The energy standard of the construction and technical installations should at least satisfy the energy goals as defined in the passive house standard NS 3700/NS3701, if special circumstances argue against it. The entire energy supply for space and DHW heating should be based on renewable energy sources with zero net emissions of climate gases during the building operation.
ZEB-O	Zero Energy Building – Operation. The energy standard of the construction and technical installations should be at least as good as for ZEHB. The entire energy supply for building operation should be based on renewable energy sources with zero net emissions of climate gases during the building operation.
ZEB-O-EQ	Same as ZEB-O, but where the energy post for equipment* is not taken into account in the zero emission balance calculation.
ZEB-O&M	Zero Energy Building – Operation and Materials. The energy standard of the construction and technical installations should be at least as good as for ZEB-O. The entire energy supply for building operation should be based on renewable energy sources with zero net emissions of climate gases during the building operation. In addition, the building should produce a sufficient amount of excess renewable energy to compensate for the embodied energy and relate climate gas emissions for production of all the materials and technical installations in the building.
ZEB-O&M-EQ	Same as ZEB-O&M, but where the energy post for equipment* is not taken into account in the zero emission balance calculation.

Appendix C

District heating, cost data

Table 0.2: Cost data for district heating, obtained from [14]

District heating	Costs
Total investment cost	**265841 NOK**
Annual maintenance cost	**11500 NOK/year**
Estimated lifetime	**15 years**

Pellet boilers, cost data

Table 0.3: Cost and technical data for pellet boilers, three alternatives obtained from [14]

Boiler model	ETA PC 20	18 kW Boiler (linear assumption)
Product price	71500 NOK	-
Pellets silo system	125000 NOK	-
Equipment mounting	20000 NOK	-
Subsides	10000 NOK	-
Total investment cost	206500 NOK	**185850 NOK**
Efficiency max load	0,948	-
Efficiency min load	0,918	-
Average efficiency	0,933	0,94
Max. heating power	20 kW	18 kW
Power consumption	73 W	-
Annual maintenance cost	3111 NOK	**2800 NOK**
Lifetime	15 years	**15 years**

Appendix D

Combined heat and power, cost data

Table 0.4: Cost data for CHPs, obtained from [14]

Model	**MkV AC Gas Fired**	**18 kW CHP** (Linear assumption)
Supplier	**WhiperGEN**	
Combustion	**External Stirling engine**	
Pellets silo system	100000 NOK	-
Total investment cost including installation	226208,9 NOK	**290840 NOK**
Price per kW	161570,8 NOK/kW	-
Max. thermal production	14 kW	18 kW
Annual maintenance cost	3700 NOK/year	**4760 NOK/year**
Lifetime	15 years	**15 years**

It should be noted that this models mainly work with natural gas; however CHP calculations are done with pellets.

Solar thermal, cost data

Table 0.5: Cost data and technical data for ST, obtained from [14]

Supplier	**SGP Varmeteknikk AS Vacuum pipes**
Price per area*	**4698 NOK/m^2**
Size per panel	1,79 m^2
Optical efficiency	61,1%
Heat loss coefficient a1	0,84 W/m^{2}k
Heat loss coefficient a2	0,0053 W/m^{2}k^2
Liquid type	Ethylene glycol (Tyfocor)
Liquid freezing point	-32 ºC
Buffer tank	OSO RTV E 300
Lifetime	**20 years**

*** Including pipes, customer central, etc. Mounting cost (20% of investment cost) will be added in the calculation. Hot water tank is not included.**

Appendix E

Reversible air/water heat pump, cost data

Table 0.6: Cost data for reversible ASHP, obtained from ABK klimaprodukter

Supplier	**ABK klimaprodukter**
Model	**NIBE F2040+VVM 500/400V** 18 kW reversible air-to-water heat pump unit at 0/35 ºC (heating mode)
Price per kW	11667 NOK/kW
Investment cost*	**210000 NOK**
Annual maintenance cost	**2500 NOK/year**
Lifetime	**10 years**

***Including VAT**

Reversible brine/water heat pump, cost data

Table 0.7: Cost data for GSHP, obtained from ABK klimaproduckter

Supplier	**ABK klimaprodukter**
Model	**NIBE 1145 + VAP 300/200** 18 kW brine-to-water heat pump unit at 0/35 ºC (heating mode)
Price per kW	7778 NOK
Price for boreholes and accumulator	180000 NOK
Investment cost**	**320000 NOK**
Annual maintenance cost	**2500 NOK/year**
Lifetime	**15 years**

****Including 2x180 m boreholes, accumulator and VAT**

Appendix F

Chillers, cost data

Table 0.8: Cost data for chillers, obtained from ABK klimaprodukter

Supplier	**ABK klimaprodukter**
Model	**NIBE 1345 VPA 300/200** Approx. 30 kW liquid chiller unit at 7/12 ºC and 45ºC (cooling mode)
Price per kW	6000 NOK/kW
Investment cost*	**180000 NOK**
Annual maintenance cost	**2500 NOK/year**
Lifetime	**15 years**
Model	**NIBE 1145 + VPA 300/200** Approx. 18 kW liquid chiller unit at 7/12 ºC and 45ºC (cooling mode)
Price per kW	7778 NOK/kW
Investment cost*	**140000 NOK**
Annual maintenance cost	**2500 NOK/year**
Lifetime	**15 years**

***Including VAT**

Electric boilers, cost data

Table 0.9: Cost data for electric boiler, obtained from OSO Hotwater

Model	**OSO universal 81R 300l-60kW**
Dimensions	ø 580 x 1600H
Investment cost*	**30000 NOK**
Maintenances cost	**2300 NOK/year**
Lifetime	**15 years**

***Including VAT**

Appendix G

Photovoltaic, cost data

Table 0.10: Cost data for PV, three alternatives obtained from [14]

Supplier	**REC Eltek**	**REC SMA**	**SunPower SMA**
Length	1,665 m	1,665 m	1,559 m
Width	0,991 m	0,991 m	1,046 m
Power	250 Wp	250 Wp	327 Wp
Efficiency	15,15%	15,15%	20,05%
Module price	750 €/kWp	750 €/kWp	1140 €/kWp
Inverter	297,14 €/kWp	210 €/kWp	210 €/kWp
Mounting system	250 €/kWp	250 €/kWp	188,9 €/kWp
Montage	200 €/kWp	200 €/kWp	151,12 €/kWp
DC cables	214 €/kWp	214 €/kWp	161,69 €/kWp
AC cables	131,2 €/kWp	131,2 €/kWp	99,13 €/kWp
Communication	40 €/kWp	40 €/kWp	30,22 €/kWp
Total BoS cost	1332,34 €/kWp	1045,2 €/kWp	841,06 €/kWp
Total investment cost	1882,34 €/kWp **14011*NOK/kWp**	1795.2 €/kWp 13362* NOK/kWp	1981,06 €/kWp 14745* NOK/kWp
Module maintenance	1593 NOK/year	1458 NOK/year	2955 NOK/year
Inverter repair	2157 NOK/five year	2031 NOK/five year	2180 NOK/five year
Annual maintenance cost	**2024,4 NOK/year**	1864,2 NOK/year	3391 NOK/year
Lifetime	**20 years**	20 years	20 years

***This currency change is variable, but it will be used the same that in [14] /Even if the efficiency is 15.15%, it has been simulated with 17.9%, an efficiency in accordance with current technologies.**

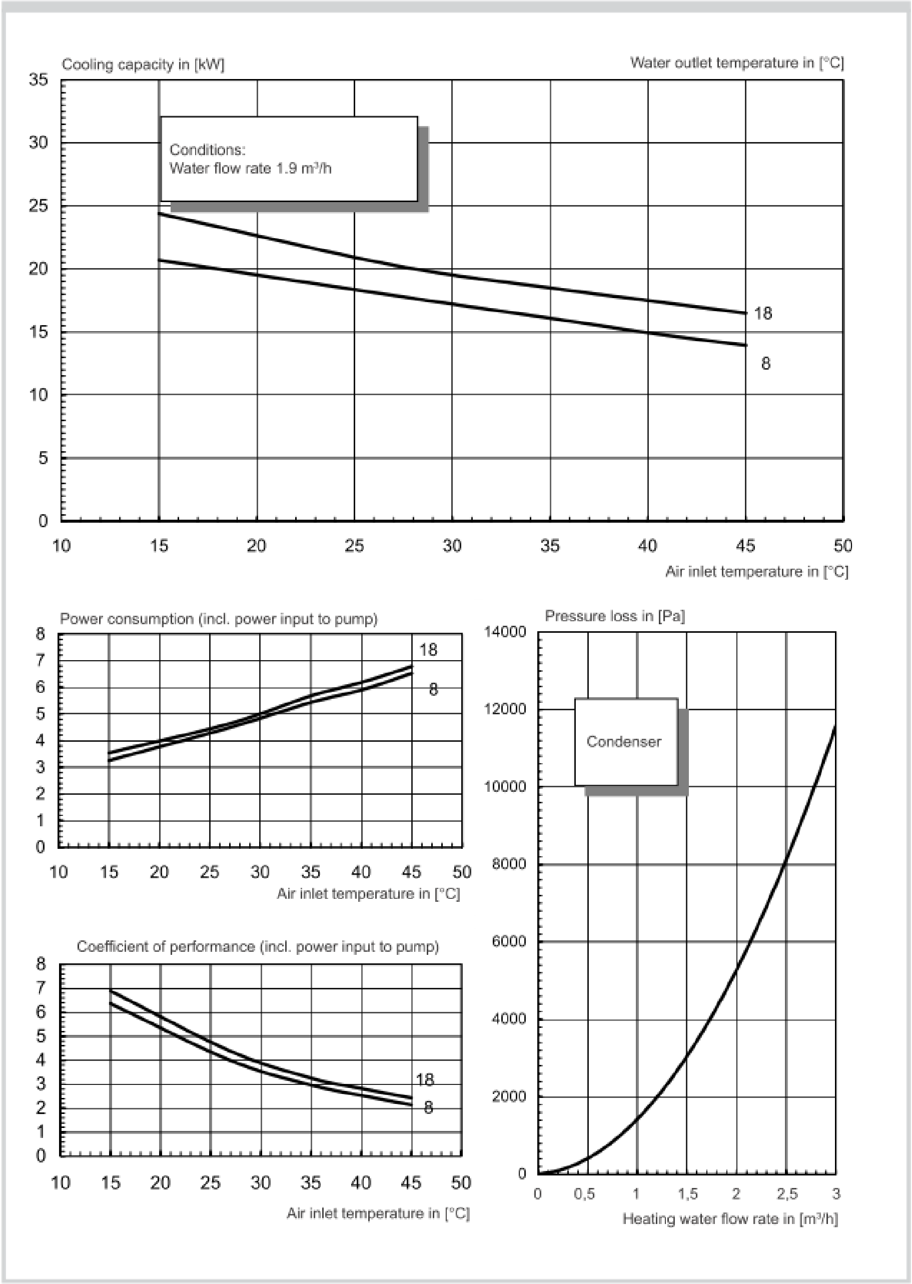
Appendix H

ASHP curves

Figure 0.2: Manufacturer's performance curves for the air source heat pump [56]

APPENDIX: 12.3 SCHEMATICS

12.3.10 Cooling mode LA 16TR



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