NTNU – Trondheim
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Smart and Cost efficient Energy Interactions in Building Complexes

Smarte og kostnadseffektive
energiinteraksjoner i bygningskomplekser

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Master's Thesis
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MASTER THESIS

for

Student Stefan Schumacher

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Smart and cost efficient energy interactions in building complexes
Smarte og kostnadseffektive energiinteraksjoner i bygningskomplekser

Background and objective

Easy access to reliable low cost energy has been an important parameter in developing the high living standard in industrialised countries. This has resulted in a tremendous increase in energy use worldwide. Increased energy efficiency is one of the most important measures to curb greenhouse gas emissions (GHG) and secure future energy supply. IEA has come out with the general term Negawatt (Energy not used) to describe energy efficiency options. There is an extensive focus on improving energy performance of buildings and reducing the primary energy use by enforcing legislation like building legislation. This brings about a completely new set of boundary conditions for design and operation of energy interaction in buildings. Energy efficiency can also be seen as a major energy source and an opportunity for value creation. Increased utilization of surplus heat/cool has been pinpointed by the Norwegian Energy21-report3 as an important strategic research area.

The objective of this work is to look into the different sub-systems of such an interconnected energy system for the investment and Life cycle cost point of view. The goal in future building projects, where several buildings with different functions are connected, is the utilization of surplus heat and efficient interaction between energy demand, surplus heat/cold and thermal storage in the building complexes..

The following tasks are to be considered:

1. Literature on review energy interactions in buildings, third party deliverance
2. Define a case
3. Structure the different subsystems to be connected (heat/cold supply, recovery, storage, distribution, etc) with respect to investment costs, LCC.
4. Develop a model to simulate the operation of the case buildings on an annual base comparing different subsystem options
5. Describe optimization methods
6. Make a scientific paper with main results from the thesis
7. Make proposal for further work

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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. The final report in Word and PDF format, scientific paper and all other material and documents should be given to the **academic supervisor** in digital format on a DVD/CD-rom or memory stick at the delivery of the project report.

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

Department of Energy and Process Engineering, September 16th 2014

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Preface

This Master's thesis was written during winter 2014 and spring 2015 as the final part of my MSc degree in Environmental Engineering at the Department of Energy and Process Engineering at the Norwegian University of Science and Technology (NTNU).

Many persons have contributed with information and helped me during the work on this Master's Thesis and I want to thank all of them for their support. First and foremost I would like to thank my research advisor Armin Hafner from SINTEF Energi AS who gave me the chance to write the Master's Thesis at the NTNU, for all the good advice he has given me and for always having time to discuss my questions. I would also like to thank the PhD student Daniel Rhode from NTNU and the research scientist Hanne Kauko from SINTEF Energi AS who helped me to get fast into the topic and all their support during writing the Master's Thesis. Further, I would like to acknowledge all people who provided me necessary data and information, all of you helped me a lot.

I would like to give a special thanks to my family for believing in me and for their financial support and my girlfriend Ingrid Dyrhaug who supported me and helped me in many different ways during this work.

Last but not least I want to thank all my fellow students and professors who accompanied me during all my studies, gave me support, inspired and motivated me.

Trondheim, May 2015.

Stefan Schumacher

Abstract

Efforts of the extension of new energy sources from renewable energies are motivated by the strategy of Energi21, which was published in 2014 by the Norwegian Ministry of Petroleum and Energy. The intention of this study is to fulfill the ambitions of the Energi21 strategy. The study is based on the building project in the Risvollan district of Trondheim, Norway. The building project includes a kindergarten, apartment building, assisted accommodation, care home and the existing Risvollan Center with shopping and healthcare floor.

An energy analysis based on the software program SIMIEN provides information about the expected heat and cold demand of the Risvollan buildings. Based on this energy analysis and the applicable technologies for covering the thermal energy demand of the buildings, three energy concepts are designed. Operation methods of each energy concepts are discussed and the system components are dimensioned.

Assessments of the energy efficiency of the three energy concepts are made. The energy efficiency ratios are decisive for the calculations of the expected annual costs. The Levelized Energy Costs (LEC) are made in order to compare the energy concepts from an economically point of view.

The conclusion of this study shows that all three energy concepts are able to meet the target of covering the Risvollan project buildings with sufficient thermal energy. The LEC analysis has shown that during the system lifetime of 25 years the higher investment costs of the exploitation of the renewable energy sources for producing thermal energy is advantageous compared to the purchase of external thermal energy.

Sammendrag

Intensjonen til denne masteroppgaven er å oppfylle ambisjonene i Energi21-strategien publisert av olje- og energidepartementet i 2014. Denne strategien tar sikte på å bruke nye fornybare energikilder i bygninger. Studien omhandler byggeprosjektet som er under planlegging på Risvollan i Trondheim. Der skal det oppføres et bygningskompleks som inkluderer barnehage, boliger, omsorgsboliger og sykehjem, i tillegg til det eksisterende Risvollansenteret som inneholder forretninger og helsesenter.

Energianalysen av det planlagte bygningskomplekset er basert på softwaren SIMIEN som estimerer varme- og kuldebehovet til bygningene. Basert på denne energianalysen og tilgjengelig teknologi som kan benyttes for å dekke behovet for termisk energi, er det utarbeidet tre energikonsepter.

Vurderinger av energieffektivitet er gjort for de tre konseptene. Energieffektiviteten er avgjørende for å beregne de forventede årlige kostnadene. Levelized Energy Costs (LEC) er brukt for å sammenligne de tre konseptene fra et økonomisk synspunkt

Konklusjonen i studiet er at alle de tre energikonseptene dekker behovet for termisk energi i bygningene. LEC-analysen viser at høye investeringskostnader for å produsere termisk energi i bygningene er fordelaktig i forhold til å kjøpe eksternt produsert termisk energi over 25 år.

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Abbreviations

BRA	Bruksareal (effective area)
BTES	Borehole Thermal Energy Storage
COP	Coefficient of Performance
CTES	Cold Thermal Energy Storage
DH	District Heating
DHW	Domestic Hot Water
DIN	Deutsche Industrie Norm (German industrial Standard)
EED	Energy Earth Designer
EER	Energy Efficiency Ratio
EN	European Norm
EU	European Union
GHG	Greenhouse Gases
GSHP	Ground Source Heat Pump
HSPF	Heating Season Performance Factor
ISO	International Organization for Standardization
LCOE	Levelized Costs of Electricity
LCOH	Levelized Costs of Heat
LEC	Levelized Energy Costs
NGU	Norges geologisk undersøkelse (Norways geologic research institute)
NOK	Norwegian Krone (currency)
NPV	Net present value
NS	Norwegian Standart
NTNU	Norges teknisk-naturvitenskapelige universitet (Norwegian University of Science and Technology)
SEER	Seasonal Energy Efficiency Ratio
SFP	Specific Fan Power
SINTEF	Stiftelsen for industriell og teknisk forskning (The Foundation for Scientific and Industrial Research)
SPF	Season Performance Factor
TES	Thermal Energy Storage
UTES	Underground Thermal Energy Storage
VAT	Value-added tax
VDI	Verein Deutscher Ingenieure (Associaction of German Engineers)

1 Introduction

1.1 Motivation

In 2008, the European Union (EU) adopted an integrated energy and climate change policy, which included targets towards the year 2020 (European Commission, 2010). The targets are known as the 20-20-20-targets:

- 20% cut of GHG emissions from 1990s levels
- 20% renewable resources into the EU energy consumption mix
- 20% reduction in primary energy use with respect to projected levels

While in Germany the use of renewable energy means minimizing the use of fossil energy it is for Norway the exploitation of the new renewable energy sources. The reason are the different energy profiles of these countries. Norway for instance produces 97 % of their electric power from water power. The idea for expansion of renewable energy sources as well as raising energy efficiency are pinpointed in the national strategy "Energi21" established from the Norwegian Ministery of Petroleum and Energy.

The strategy of Energi21 stipulates ambitions to raise the energy efficiency in the building sector. In addition, the local and building-integrated renewable energy production should be encouraged. Hence shall be achieved a flexible integration of energy-efficient buildings into the energy system for covering the demand of electricity, heating and cooling. (Sverre Aam 2014)

The ambitions of the Energi21 strategy in energy systems is to develop energy systems with cost-effective, operationally efficient integration of renewable energy and to extend the energy production from renewable sources, distributed production and energy storage. (Sverre Aam 2014)

This brings about a completely new set of boundary conditions for design and operation of energy interaction in buildings. The department of Energy at the research institution SINTEF in cooperation with the Norwegian technical University of Trondheim (NTNU) carry these challenges of research in energy efficiency and renewable energies into execution.

1.2 Objectives

The purpose of this MSc study is to look at the Risvollan project area for supplying the planned complex of buildings with thermal energy for space heating, production of domestic hot water and space cooling.

A literature review has been made to investigate available and applicable technologies and to evaluate the technologies from an energy and cost efficient point of view. All available information of the project have been collected to make simulations with SIMIEN for discovering the heat and cold demand of all planned buildings based on the requirements of the Norwegian passive house standard NS 3701.

For further estimations about the extent and possibilities to provide thermal energy from a geothermal well grid and solar heat absorbers, all available information about the subsurface and solar irradiation of the project area have been collected and assembled.

In the energy analysis of the buildings at the Risvollan project area calculations for an estimation of the extent and feasibility of the available technologies have been made. All calculations and estimations are based on the SIMIEN calculations for the thermal energy demand. The required size of a geothermal well grid has been simulated with the computer software “Energy Earth Designer (EED)”. The usable rooftop area for solar heat absorbers has been determined under the consideration of unusable shadow area and the efficiency factors of the absorbers.

Three energy concepts are designed for covering the thermal energy demand of the buildings in the Risvollan project area. The concepts are based on the considered technologies and their calculations for dimensioning. The three energy concepts includes a geothermal well grid, solar heat absorbers, an ice TES and the supply from the district heating grid. For evaluating the expected energy efficiency there are made predictions about the system ratios for heating and cooling. The calculation of the dimensions of the system components are made and are the basic data for the Levelized energy cost analysis (LEC) for the lifetime of 25 years for heating systems.

The calculated LEC of the three energy concepts are compared and evaluated for an economically assessment.

1.3 Content outline

The whole study is divided in 9 chapters. Chapter 1 is the introduction that covers the motivation of the study, objectives of the study and the content outlines.

Chapter 2 of this Master’s Thesis includes the literature review. The sources and components of thermal energy production are considered as well as frame conditions and evaluation methods of energy and cost efficiency.

In chapter 3, all frame conditions and available information of the Risvollan project are collected and assembled. The consideration of the project includes the conditions of the subsurface, available information about the planned Risvollan project area, details about the planned buildings and data about the expected solar irradiation in Trondheim.

Simulations with the software SIMIEN for the expected heat and cold demand of the Risvollan buildings are made in in chapter 4. An analysis of the energy availability from the thermal energy sources are made. The analysis includes calculations about the solar yield of the roof top area and a simulation with the computer software Energy Earth Designer (EED) for figuring out the underground conditions for a geothermal well grid.

Three possible concept variants for supplying the Risvollan project buildings with thermal energy during the changing annual demand are designed in Chapter 5. The concepts include all mentioned thermal energy sources and system components from chapter 2. All concept components are dimensioned as accurate as possible based on the available information.

In chapter 6 the LEC of each concept is calculated. Frame conditions are explained and all available cost and price information is included.

A final discussion of all concepts and results including a consideration of the data quality is made in chapter 7. The summery of the entire study as well as recommendation for further work is covered in the chapter 8. The final chapter 9 includes the Publication bibliography.

2 Background theory

2.1 Thermal energy sources, storage and system components

Thermal energy in the building sector is mainly used for heating, cooling and the production of domestic hot water. The annual thermal energy demand varies seasonally. In northern Europe the heat demand decreases considerably during winter while cold energy during the summer month is needed. However, heat energy offered by the sun is mainly available during the summer, while cold energy is climate-related rather disposable during the winter months. A smart energy system closes the gap of that mismatch.

Thermal energy storage (TES) is one of the key technologies for energy conservation and therefore, it is of great practical importance. One of its main advantages is that it is best suited for heating and cooling thermal applications. (Dinçer, Rosen 2011)

For designing suitable energy concepts, it is important to find applicable thermal energy sources and storage system for the considered Risvollan project area. Theoretical applicable thermal energy sources and storage systems are considered in the following chapters.

2.1.1 Heat pump

The first impulse for using heat pumps has been delivered by the need of cooling food in order to increase its storage life during transportation. Nowadays heat pumps are used for heating as well as cooling tasks in a bright range of application. (Banks 2012)

By applying technical work to the heat pump, it moves heat energy from a low temperature level to a level at higher temperature. (Huggins 2010) An amount of external power (approx. 25 %), mostly electrical energy, is used to accomplish the energy transformation from the heat source to the heat sink. The heat pump cycle is a closed system and consists of two heat exchangers, the condenser and the evaporator, an expansions valve and a compressor. A refrigerant circulates inside the so-called vapor-compression-cycle. A heat pump cycle with all components is shown in Figure 1.

The refrigerant flows from the compressor through the condenser and changes the status from gaseous into liquid while giving off the heat to the heating system. After the condenser, the refrigerant passes the expansion valve where it cools down and transforms partially from liquid into vapor. The refrigerant flows through the evaporator, absorbs heat from the heat source, and evaporates completely.

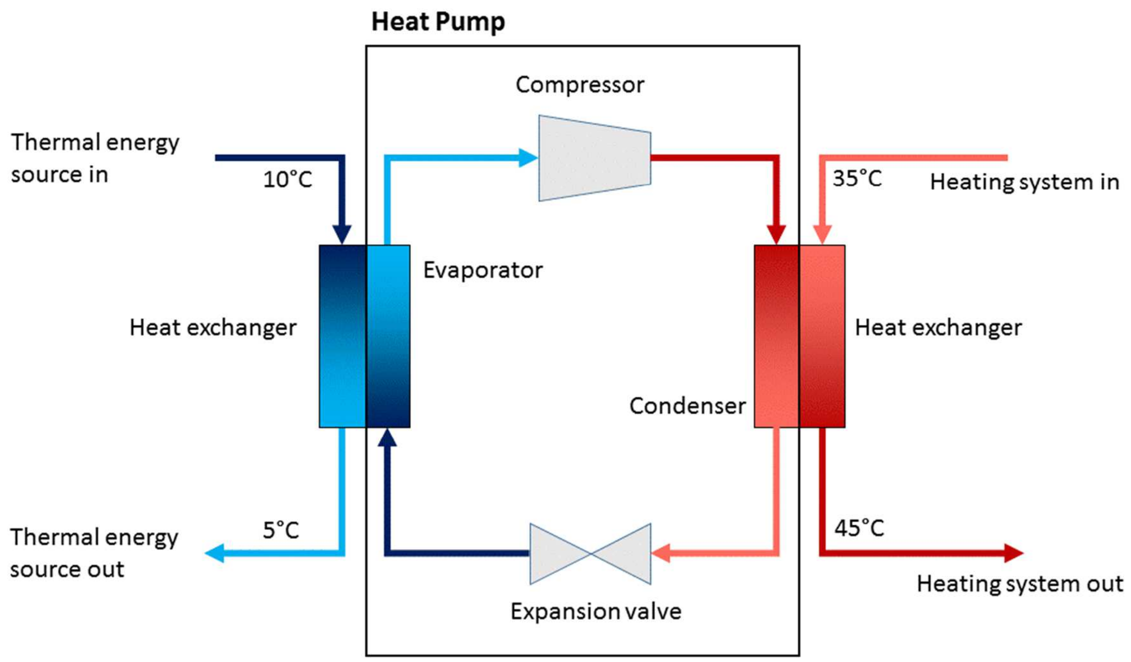

Figure 1: The heat pump system

Now, the refrigerant is compressed from a low-pressure to a high-pressure gaseous state. During compression, the refrigerant is heated again.

A reversible type of a heat pump is able to reverse the cycles flow. Than the evaporator and the condenser switch its function and the system can be used for cooling. Thus, a reversible type can be used to provide heat in the winter and cold in the summer.

2.1.2 Geothermal energy

Humans have been using geothermal Energy for several 1000 year. In 1791 Alexander von Humboldt ascertained that the temperature increase by the geothermal gradient of 3,8°C per 100 m depth in Freiberg's mining area. (Stober, Bucher 2014)

Geothermal energy is the stored energy in the form of heat beneath the surface of solid earth. (Banks 2012) Nowadays, a common technique to use geothermal energy is the extraction of heat from boreholes. A distinction is made between the shallow geothermic up to 400 m and deep geothermic from 400 m until over 1,000 m. (Stober, Bucher 2014)

In order to use the heat from shallow geothermal wells for space heating in buildings it is necessary to extract the heating energy of the underground by heat pumps. Various shallow geothermal system like geothermal collectors (horizontal loops), borehole heat exchanger (vertical loop), energy piles, and groundwater wells can be used to extract and/or store heat from the underground (Stober, Bucher 2014). A BHE system with vertical loop is shown in Figure 2.

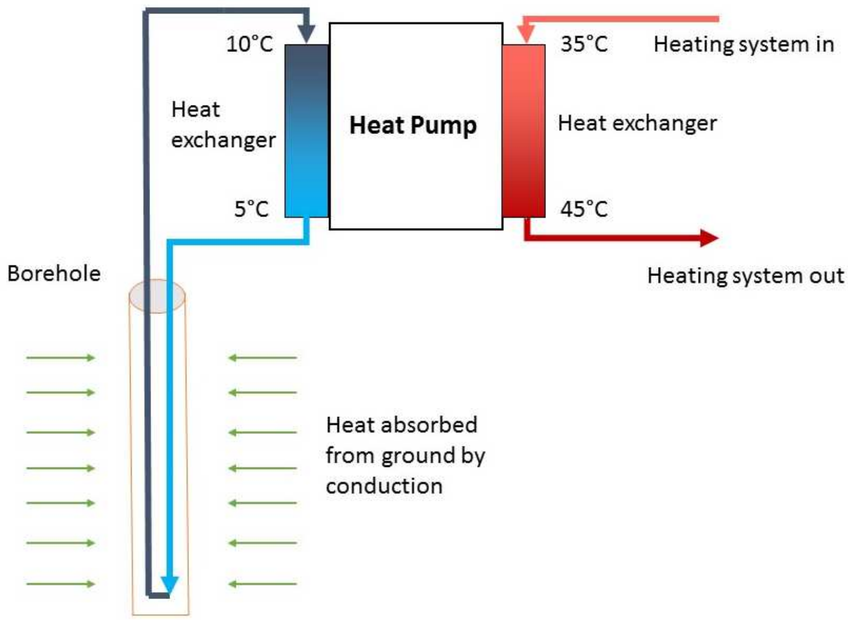

Figure 2: The borehole heat exchanger system

A borehole heat exchanger (BHE) is a system consisting of tubes, which are installed, in a borehole and in which a heat transfer fluid circulates. Types of tube systems are single-U, double-U, triple-U and coaxial tubes. The usually used type is the double-U tube. (Stober, Bucher 2014)

The BHE receives heat supply from the borehole's surrounding and depends on the thermal conductivity of the underground. The individual thermic conductivity of a boreholes surrounding can be measured by the standard method called Thermal Response Test. The length of a borehole depends mainly on the necessary heat demand and the thermal properties of the underground (Stober, Bucher 2014). Preliminary research results have confirmed that the thermal conductivity of the rock mass and grout have the greatest impact on the efficiency of underground thermal energy storage (Wołoszyn, Gołaś 2014). A recommendation about the specific heat extraction from different underground types are listet from VDI 4640 for 1,800 h and 2,400 h operation time during one year and is shown in Figure 3.

Underground	Specific heat extraction	
	for 1800 h	for 2400 h
General guideline values:		
Poor underground (dry sediment) (λ < 1.5 W/(m · K))	25 W/m	20 W/m
Normal rocky underground and water saturated sediment (λ < 1.5–3.0 W/(m · K))	60 W/m	50 W/m
Consolidated rock with high thermal conductivity (λ > 3.0 W/(m · K))	84 W/m	70 W/m
Individual rocks:		
Gravel, sand, dry	< 25 W/m	< 20 W/m
Gravel, sand, saturated water	65–80 W/m	55–65 W/m
For strong groundwater flow in gravel and sand, for individual systems	80–100 W/m	80–100 W/m
Clay, loam, damp	35–50 W/m	30–40 W/m
Limestone (massif)	55–70 W/m	45–60 W/m
Sandstone	65–80 W/m	55–65 W/m
Siliceous magmatite (e.g. granite)	65–85 W/m	55–70 W/m
Basic magmatite (e.g. basalt)	40–65 W/m	35–55 W/m
Gneiss	70–85 W/m	60–70 W/m
The values can vary significantly due to rock fabric such as crevices, foliation, weathering, etc.		

Figure 3: Possible specific extraction values for BHE (VDI 4640)

Boreholes can also be used as Thermal Energy Storage (BTES). In summer season surplus heat can be injected into the underground. The underground regenerates thermally from the winter extraction and additional heat can be stored there too. However, a single borehole is efficient for neither inter-seasonal nor day/night underground thermal energy storage. BHE-fields are a system of minimum five connected BHE. BHE-fields are mostly used for seasonal heat storage but also in order to cover the cooling demand of buildings. It is recommended to maintain a constant distance around 5 m between the boreholes and the upper surface of the heat store must be thermally insulated to reduce heat losses to the atmosphere. One of the

Europe's biggest BHE-fields is the plant of Lørenskog of the Ny Ahus hospital in Norway. It consist of 350 BHE, each of them are 200 m deep.(Stober, Bucher 2014; Lanini et al. 2014)

2.1.3 Solar thermal system

Using solar thermal energy has a long tradition in the humankind's history. Nowadays, solar heat application in small scale for warm water production for instance, but also huge solar heating power plants exist. (Schabbach, Leibbrandt 2014)

The absorbing material of the solar collector absorbs the radiation energy of the sun. As a result the material's temperature increase. (Schabbach, Leibbrandt 2014) Different types of collectors such as simple heat absorber tubes, flat-plate collectors or evacuated-tube collectors are used.

The absorber of a solar collector absorbs the radiation energy of the sun and heats the through the absorber flowing liquid, mostly water with added antifreezer. Afterward the liquid flows to a facility where the heat is used directly or to a heat storage tank. (Robert Stieglitz, Volker Heinzel 2012). A simple variant of the combination of heat storage tank and solar collector is shown in Figure 5.

Even with the best alignment of the sun collectors, the maximum efficiency of 70 up to 80 % for transforming the solar irradiation into heat can be reached. Under consideration of the system temperatures and the type of the collector, the efficiency is even smaller. (Schabbach, Leibbrandt 2014)

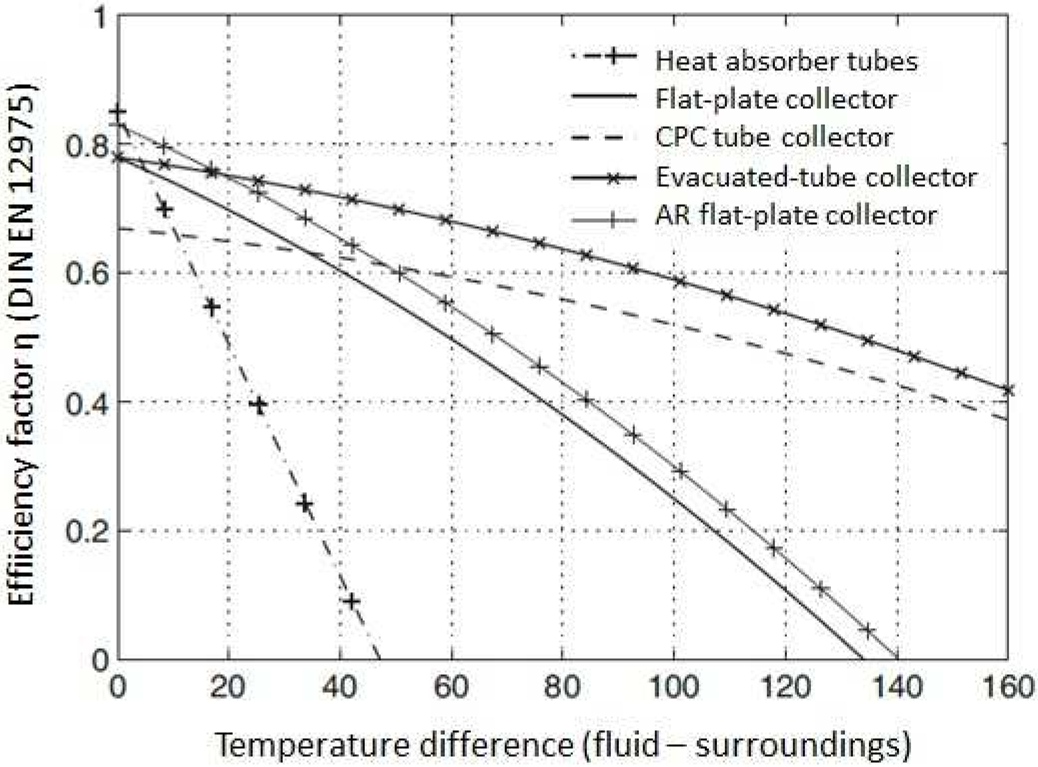

Figure 4: Efficiency factor of solar heat collectors (Schabbach, Leibbrandt 2014)

As it is shown in Figure 4, the efficiency of the different kinds of sun collectors highly depending on the difference between average fluid temperature and the surrounding temperature.

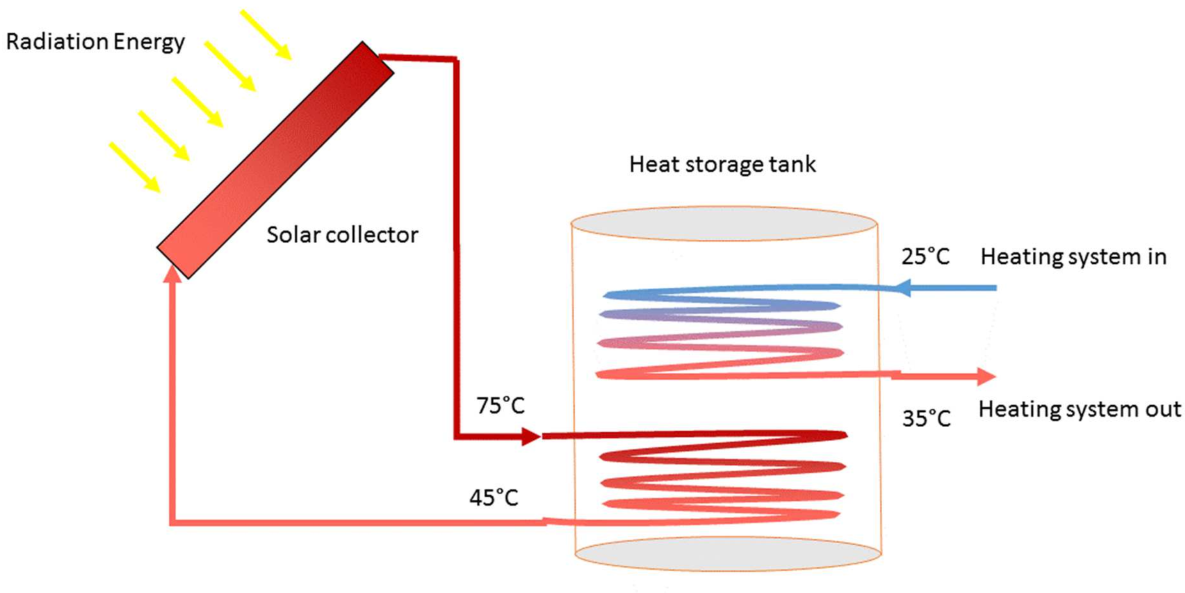

Figure 5: A solar collector with heat storage tank

The incoming radiation depends on the general atmospherically influences, the geographical location, date, time of the day and especially of the clouds. The yield of a solar plant depends mainly on the collector's area and storage dimension. In the buildings sector solar plants are mainly used for heating tap water and supporting the space heating system. (Schabbach, Leibbrandt 2014) In combination with geothermal wells, the solar energy can be used to regenerate boreholes thermally.

2.1.4 Ice thermal energy storage

The oldest example of an ice thermal energy storage (CTES) is to harvest ice from lakes and rivers and storing it in a well-insulated warehouse for using it for preserving food, cooling drinks, and air conditioning. (Dinçer, Rosen 2011)

Thermal energy storage (TES) means conserving of energy for later use. If a material releases or absorbs heat energy while the temperature of the material increases or reduces, than it is sensible heat and can be calculated by the first law of thermodynamic:

$$Q_{1-2} = m \cdot c_p \cdot (T_2 - T_1)$$

If the heat storage material involves phase transitions during absorbing or releasing energy, than the energy used for the transition is called latent heat. The required energy to convert ice to water is called heat of fusion. The phase changing process during absorbing or releasing latent heat happens without changing the materials temperature. (Dinçer, Rosen 2011; Huggins 2010)

An ice TES is a water filled storage tank. Depending on the operation method, the ice TES can be used as heat or cold supplier. In case of the utilization as a heat supplier, a medium, mostly brine or refrigerant, flows through the heat exchanger coils inside the tank. The heat energy is transferred between the water inside the tank and the fluid in the coils. During the discharging mode, the water in the tank cools and the phase transition of the water into ice occurs. In the charging mode, heat energy is led into the tank, the solid ice melts and the temperature inside the tank increases. (Kalaiselvam, Parameshwaran). An ice TES system during supplying cold energy to a heat exchanger is shown in Figure 6.

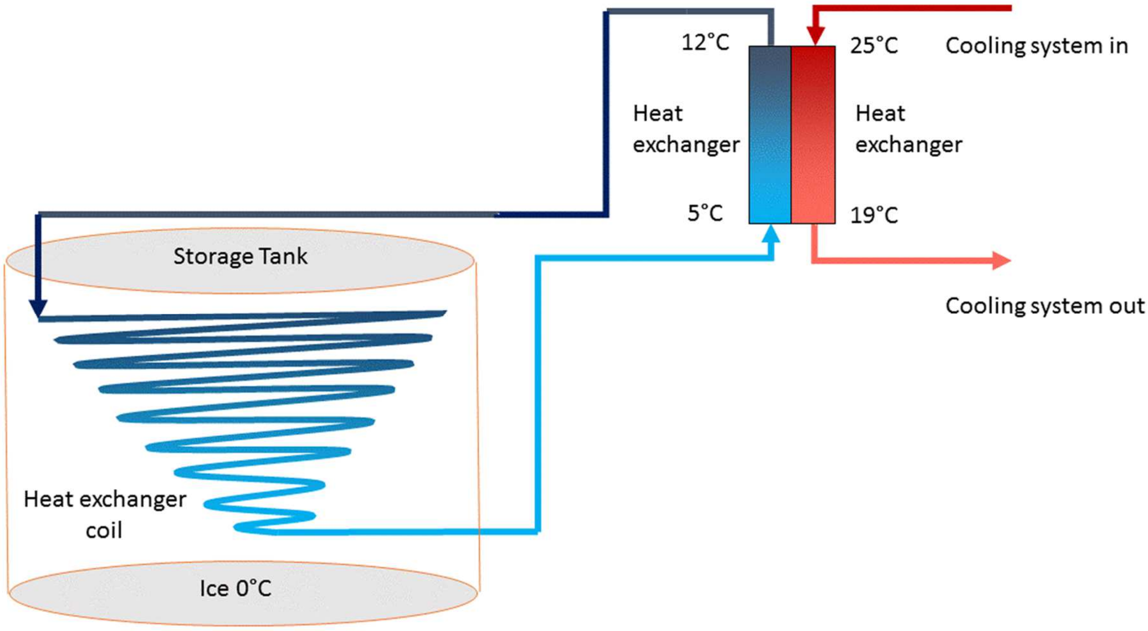

Figure 6: The ice thermal energy storage system

The cooling capacity of an ice TES system under total freezing is 18 times higher than that of a water CTES operating between 12 and 7°C. Ice TES systems require less space than water CTES systems because of the higher energy storage capacity during freezing.

$$\textbf{Water TES}: \quad 7°\text{C Water (1kg)} \underset{20{,}9\ \text{kJ}}{\Longleftrightarrow} 12°\text{C Water (1kg)} = 20.9\ \text{kJ}$$

$$\textbf{Ice TES}: \quad 0°\text{C Ice (1kg)} \underset{334{,}4\ \text{kJ}}{\Longleftrightarrow} 0°\text{C Water(1kg)} \underset{50{,}2\ \text{kJ}}{\Longleftrightarrow} 12°\text{C Water (1kg)} = 384{,}6\ \text{kJ}$$

A CTES system has a high potential for increasing the efficiency of the seasonal use of thermal energy referred to the mismatch between the supply and demand of thermal energy in buildings. The period of storage can vary from a few hours for diurnal storage cycles, to many months for seasonal (annual) cycles. A thermal applications of a CTES is cooling and air-conditioning but also space heating or supply of hot water. (Dinçer, Rosen 2011)

2.1.5 District heating

The district heating system distributes thermal energy, which is produced in a central location to a costumer unit where it can be used for heating requirements such as space heating or domestic warm water production. Energy sources for generating district heat can be manifold.

The most common sources are waste, biofuel, heat pumps, landfill gas, natural gas, propane/butane gas, electricity and fuel oil. A network provides the generated heat to the costumer. The main distribution network consists of two insulated pipes, the supply and return lines. The forward water to the costumer provides temperatures between 80°C and 120°C and the return water lines reaches temperatures from 45°C to 75°C. The heat between customer and the providing networks is usually provided by a heat exchanger. An example of a DH-grid is shown in Figure 7. A typical average of the heat losses of the providing network is around ten percent. Higher efficiency and better pollution control can be reached of district heating plants instead of localized small-scale production systems. (Statkraft 2009)

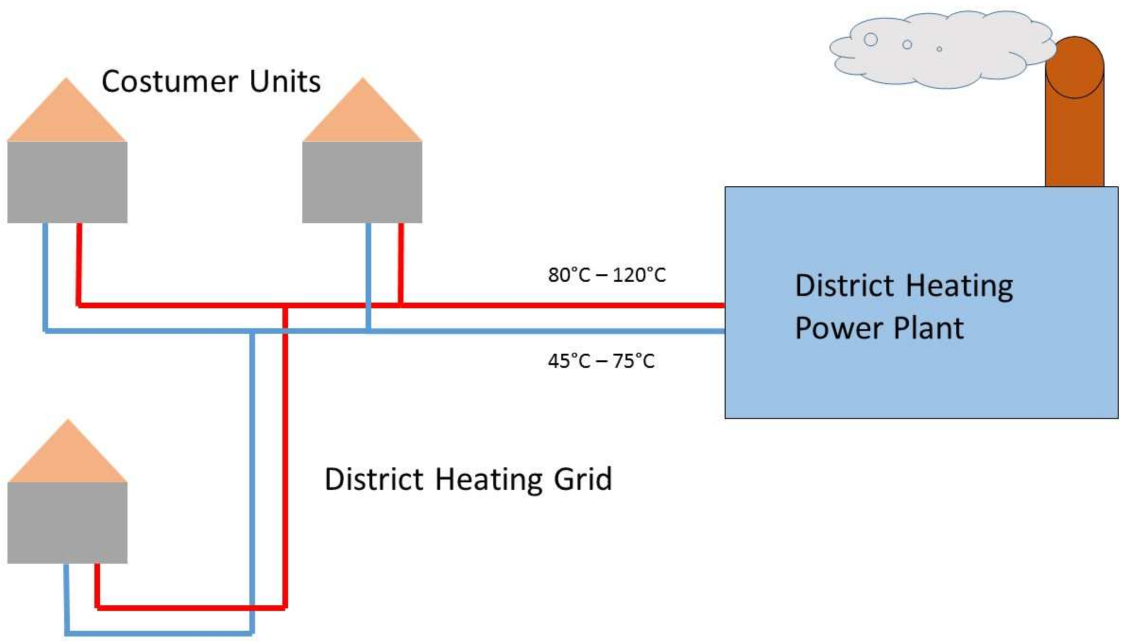

Figure 7: The district heating grid system

The heat energy for the district heating network of Trondheim is produced of nearly 70 % out of municipal solid waste. Every year the plant burns more than 200,000 tons of waste. The burnt waste comes from the entire Central Norway region, from Saltfjellet in the north to Dovre in the south. The other 30 % of the heat production is supplied by the use of bioenergy, heat pumps, gas, electricity and small amounts of oil .The plant produces 600 GWh heat a year. The entire network consists of 10 heating plants and 250 km distribution grid (Statkraft 2009)

2.2 Energy efficiency

Effectivity and Efficiency is closely related but it must be differentiated between these terms. While Effectivity is the proportion of reaching a defined target under input of all means, means Efficiency meet the target with a minimum of means. In everyday speech, it can be expressed in the following words: "Effectivity is to do the right things and efficiency is to do the right things right." (Pehnt 2010)

In the view of heat energy supply of buildings, two subsystems must be considered. On the one hand, the building consumed energy must be minimized and on the other hand, the heating system itself should run as efficient as possible. Both systems together is to understand as a total-system Building+Heating. The main aim of this system is to fulfill the comfort requirements of the user and residents. (Pehnt 2010) Heat isolation and the reuse of heat losses of buildings but also the exploitation of all heat and cold sources as well as an elaborated energy management system are necessary to fulfill the energy effectivity and efficiency of the total system.

2.2.1 Energy efficiency in buildings

The actual construction regulation (Byggteknisk forskrift) is called TEK10. The new regulation TEK15, is expected to come into force in 2015. It is expected that the requirements for new planed and constructed buildings are orientated on the passive house standard NS 3701:2012.

The actual methods and data for calculating the energy performance of buildings to meet the requirements of the TEK10 are included into the standard NS 3031. The NS 3031 includes residual buildings as well as public building types. In addition, the operation times of the different build types are included here. These times deliver information to control the heat and cold behavior between the operation times.

The passive house standard NS 3701 contains criteria for heat losses of transmission and infiltration, but also benefits from solar and internal loads are included. The building must be designed to have an annual heating demand of not more than 15 kWh/m^2 and a cooling demand of 15 kWh/m^2 or with a peak heat load of 10 W/m^2. The total primary energy consumption (heating, hot water and electricity) must not be more than 120 kWh/m^2 per year and the air leakage value of the building must not be higher than 0.6 times the house volume per hour ($n_{50} \leq 0.6/h$) at 50 Pa. The NS 3701 is valid for public buildings. (Passivhaus Institut)

2.2.2 Energy efficiency of thermal energy systems

A thermal energy system is often a very individual system, which includes different components and energy sources. Every system varies in size, components, requirements, operation methods, geographical and climatically circumstances. Energy efficiency of such a system can be measured for single components as well as for the total energy system. A consideration of the energy efficiency can be done for a fix point of time and a period. The most important parameters for an evaluation of energy efficiency are the heat output and the electrical energy input.

A heat pump is the most significant device of a thermal system. A reversible type is used for cooling and heating tasks. It is common to measure the **COP** to rate heat pump efficiency in a heating circulation system. The higher the COP is the more efficient runs a heat pump. The COP represents the efficiency to a fix point of time and shows the rate of heat output to the electrical energy input. (Stober, Bucher 2014; Wosnitza 2012)

$$\mathrm{COP} = \frac{\text{Heat Output}}{\text{Electrical Energy Input}}$$

During the year, outdoor temperatures are changing and accordingly the necessary heat requirements varies. For evaluating the efficiency of an entire heating system during a period of time, the Seasonal Performance Factor (**SPF**) can be used. The SPF includes the additional electrical energy demand of the equipment that is used to run the heating cycle. The higher the SPF is the more efficient runs heating system. (Kanoglu et al. 2012).

$$\mathrm{SPF} = \frac{\text{Total Seasonal Heating Output}}{\text{Total Electrical Energy Input}}$$

The Energy Efficiency Ratio **EER** is used to evaluate a heat pump's efficiency in the cooling cycle. Like the COP, the EER shows the efficiency of a fixed point of time. (Kanoglu et al. 2012)

$$\mathrm{EER} = \frac{\text{Cooling Capacity}}{\text{Electrical Energy Input}}$$

The Seasonal Energy Efficiency Ratio rates the seasonal cooling performance for the cooling cycle. Additional energy demand of the equipment for the cooling cycle is included. The higher the **SEER**, the more efficiently the heat pump cools. (Kanoglu et al. 2012)

$$\mathrm{SEER} = \frac{\text{Total Seasonal Cooling Output}}{\text{Total Electrical Energy Input}}$$

2.3 Levelized Energy Costs

Levelized Energy Cost (LEC) are also known as the Levelized Cost of Electricity (LCOE). LEC is a convenient tool for comparing the energy unit costs of different technologies over the economic life of the energy system. The LEC method, is used as a benchmarking tool to assess the cost-effectiveness of different energy generation technologies (IEA - International Energy Agency 2010).

The LEC includes all costs of the analyzed energy system over the system's lifetime. The calculation includes the initial investment costs, operations and maintenance costs, cost of fuel and the cost of capital. The LEC is defined as the total lifetime cost of an investment divided by the cumulated generated energy by this investment (Pawel 2014). The equation of the LEC is defined as follow: (Hernández-Moro, Martínez-Duart 2013)

$$LEC = \frac{\left(\sum_{n=0}^{N} \frac{Costs_n}{(1+r)^n}\right)}{\left(\sum_{n=0}^{N} \frac{E_n}{(1+r)^n}\right)}$$

The costs consists of the Investment expenditures in year *n*, operations and maintenance expenditures in year *n* and the Fuel expenditures in year *n*. E_n is the energy generation in year *n*, *r* is the discount rate and *N* is the lifetime of the system. The summation starts with *n*=0. If the entire initial costs for building the energy system are invested once at the beginning of the first year, than the initial costs can be excluded of the running costs. In that case the calculation starts with n=1 (Hernández-Moro, Martínez-Duart 2013).

$$LEC = \frac{\left(Initial\ Costs + \sum_{n=0}^{N} \frac{Annual\ Costs_n}{(1+r)^n}\right)}{\sum_{n=0}^{N} \frac{E_n}{(1+r)^n}}$$

The calculation method of the discount rate *r* depends on the financing method. In case of financing with outside borrowed capital it must be calculated like in the following equation: (David Keeping, Sintef 2007)

$$r_G = \frac{1}{(1+e)} \cdot \left[\frac{r_n(1-s)-i}{(1+i)} - e\right]$$

i means the inflation, *s* the tax rate, *e* is for rate of price increase and r_n stands for the nominal interest rate. In case of self-financing, the tax rate falls away and the equation can be shortened to: (David Keeping, Sintef 2007)

$$r_E = \frac{1}{(1+e)} \cdot \left[\frac{r_n - i}{(1+i)} - e\right]$$

A typically LCE is calculated over 20 to 40 year lifetime. The unit of LEC is given in the country specific currency per kilowatt-hour, for example EUR/kWh, Kr/kWh or $/kWh. LEC studies are very individual and are highly dependent on the different sources of the information. The quality and validity are dependent on the assumptions, financing terms and the analyzed technological deployment. For a comparison of the LECs for different systems, it is very important to define the systems boundaries. (IEA - International Energy Agency 2010)

An alternative but mathematically identical approach is the calculation method of the net present value (NPV). The LEC is the average internal price at which the energy is to be sold in order to achieve a zero NPV. (Pawel 2014)

3 Project frame conditions

The contents of chapter three are the conditions of the subsurface, the solar irradiation and the available data for the planned buildings in the Risvollan project area. The considerations are the basic information for simulating the heating and cooling demand of the buildings in the Risvollan project area, for dimensioning the geothermal well grid, the solar heating system and the ice TES.

3.1 Subsurface

The district of Risvollan in Trondheim is situated in the south of the city, 5 km southwards from the city center. The area of Risvollan is mainly used as a residential area and the biggest housing cooperative of Norway is located here.

Multiconsult AS, Rambøll Norge AS and the Trondheim municipality did a geotechnical investigation about the Risvollan Center area in 2008 and 2013. The project area lies between 125 – 130 m above the sea-level. The terrain falls from north, west and south but rises slightly to northeast. The Risvollan project area is located between two quick clay zones, which are called Risvollan and Blakli Kvikkleiresone. The map of the quick clay zones is shown in Figure 8. The Risvollan Kvikkleiresone located north of the project area, shows a 2-3 m thick crust of clay. Beneath the topmost crust of clay fellows a tighter clay layer. (Trondheim Kommune 2013)

The upper layer consists of different kinds of clay before the bedrock starts. The bedrock, which consists of green stone and greenschist includes layer of quartzite. Green stone and greenschist are a basic magmatit (Norges geologiske undersøkelse (NGU)). The deepest test drilling “MU2_1” is located in the southeast of the Risvollan project area. The depth of this drilling is approximately 51 m deep. The location of the test drilling MU2_1 is shown in Figure 8. During test drilling of MU2_1, they have not reached the bedrock layer. (Trondheim Kommune 2013)

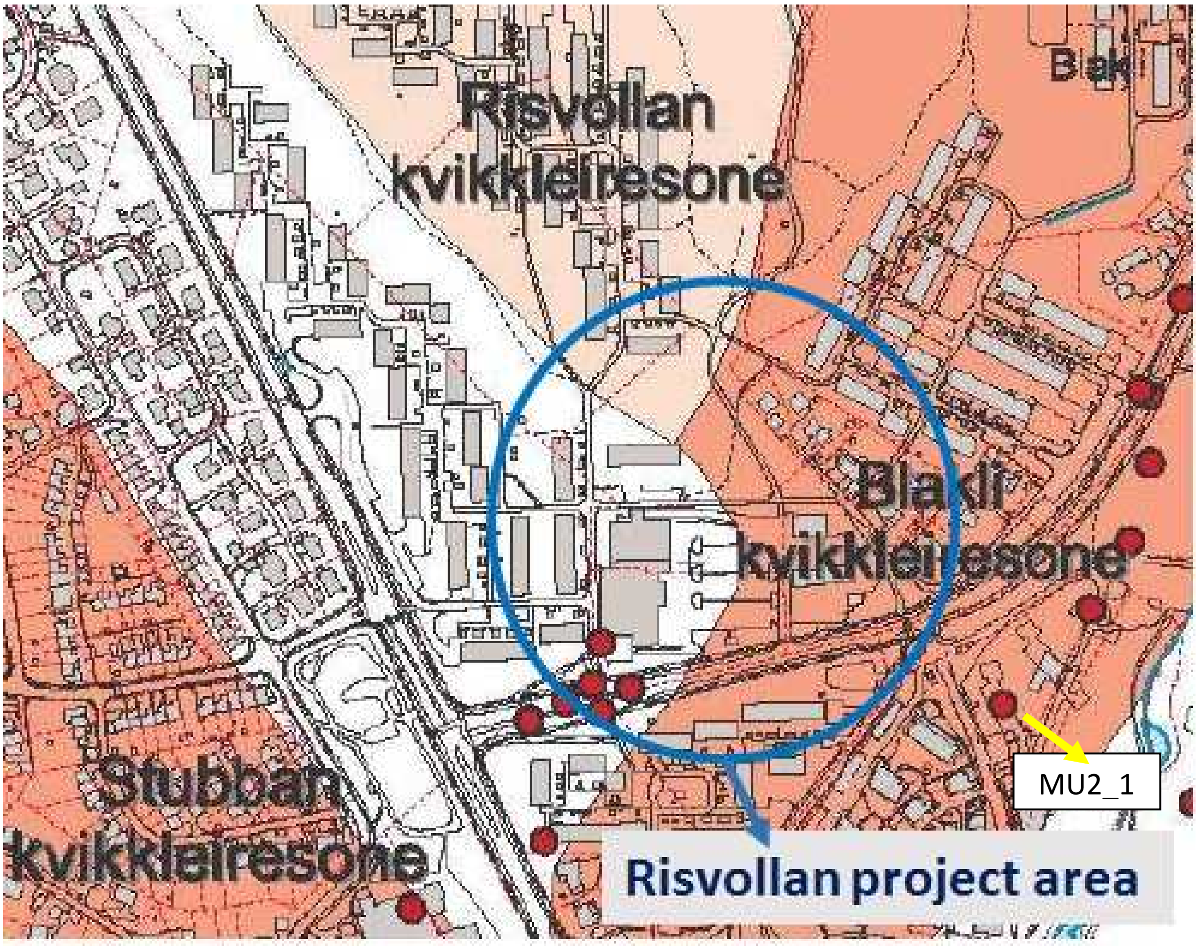

Figure 8: Clay zones of the Risvollan project area

Special cases are needed for drilling a well during the top layer of clay before it comes into the bedrock where the rock stabilizes the well itself. The drilling work through the clay layer is more expensive than drilling in the bedrock because of the steel cases.

The already existing boreholes around the Risvollan area are shown in Figure 9 and are marked with blue points. The map and the available data about the boreholes are provided from NGU (Norges geologiske undersøkelse). The depth from the surface to the rockbed of these boreholes is varying between 0.5 m and 84 m irregular, so that it is not possible to make a useful prediction about the expected depth to the rockbed in the project area.

In chapter 6, will be used the maximal reached depth of 51 m during test drilling MU2_1 as reference value for the thickness of the clay layer.

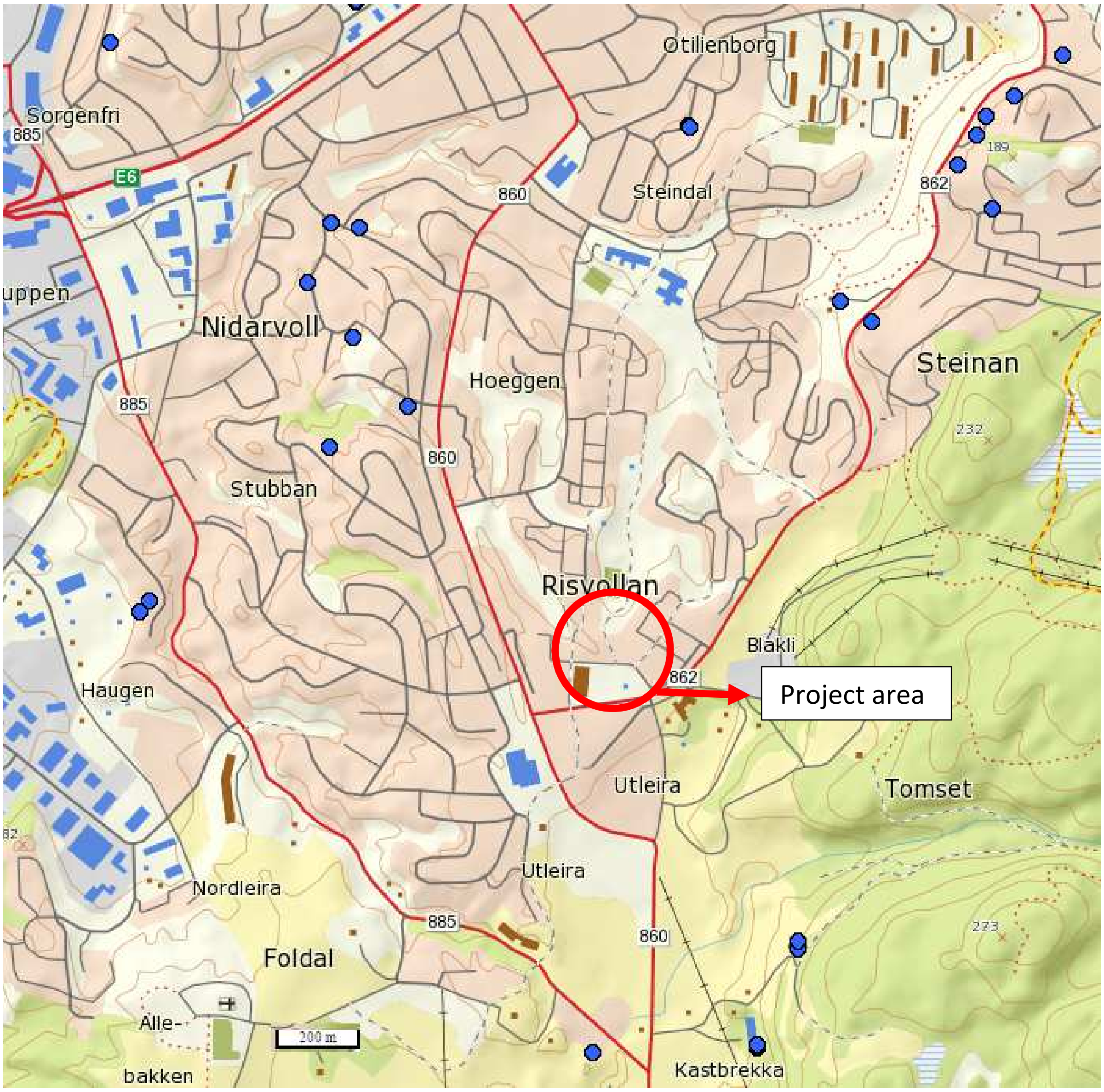

Figure 9: Existing boreholes at Risvollan area

3.2 Buildings

The buildings of the Risvollan project are planned in the area between the streets "Blaklivegen" and "Utleiervegen" of Trondheim. The plans consisting a kindergarten in the northeast, care homes in the east, the assisted accommodations in the south and a residential building in the northwest. The existing Risvollan center includes a shopping and healthcare floor and is going to be modified. The four apartment's in the middle of the construction plan are optional and their construction depending on the future freehold conditions.

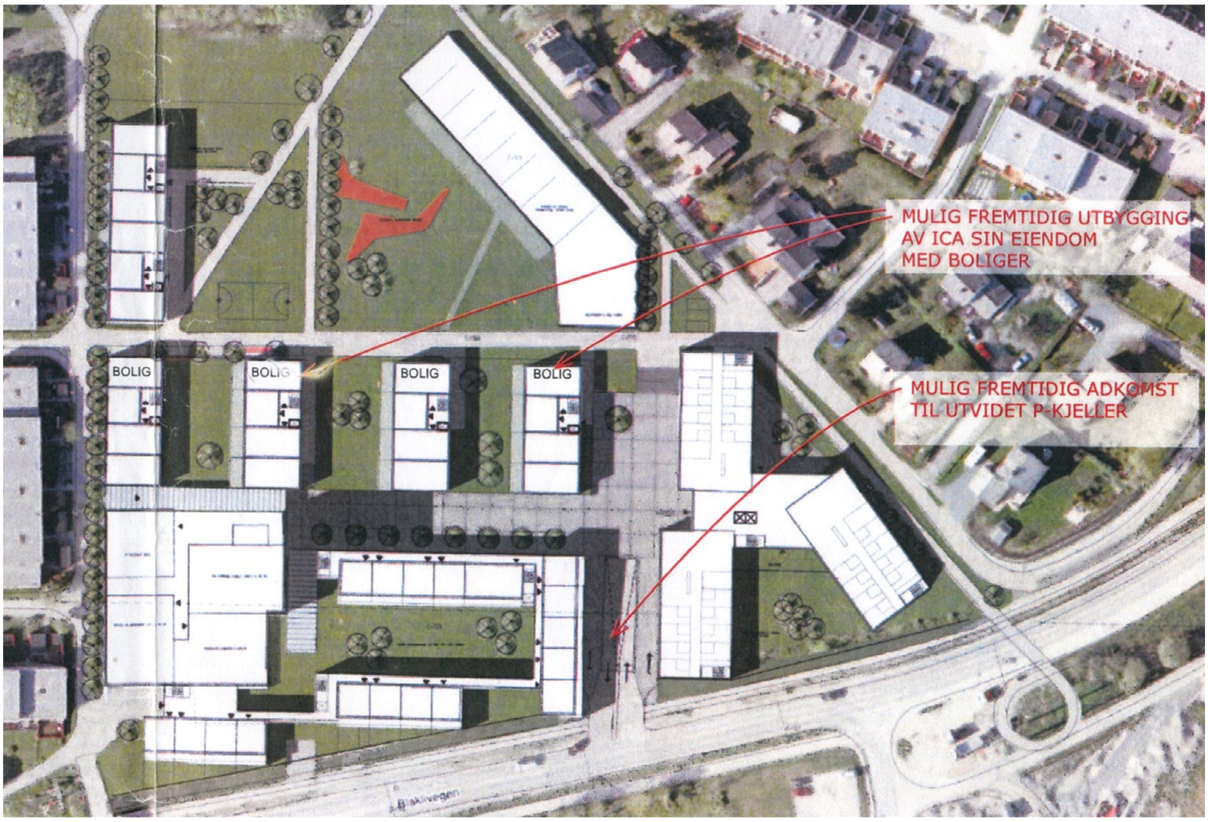

Figure 10: The Risvollan project area

3.2.1 Kindergarten and social service building

The kindergarten located in northeast of the areal provides 1,000 m^2 living space on two floors and is shown in Figure 11. The social service building of the Risvollan housing cooperative is connected with the kindergarten and offers a 400 m^2 space.

Figure 11: Kindergarten and social service building

The operation time of the kindergarten is ten hours a day and 5 days a week. The whole facade of the building consist of 20 % windows and additional 15 m^2 doors. More details about the kindergarten and social service building are shown in Table 1.

Table 1: Kindergarten and social service building

Kindergarten and social service building		
Effective area (BRA)	1,400 m^2	1,000 m^2 Kindergarten, 400 m^2 social service
Facade area	1,088 m^2	Thereof 15 m^2 doors
Window area	20%	120 windows (each 1.60 m x 1.20 m)
Heating volume	4,760 m^3	
Number of floors	2	Floor level: 3.4 m
Roof	700 m^2	Flat roof
Ground	700 m^2	Ground floor to soil

3.2.2 Apartments north

The apartments building is located in the north of the area. Three floors with 18 apartments provide a total living area of 1,620 m2 and is shown in Figure 12.

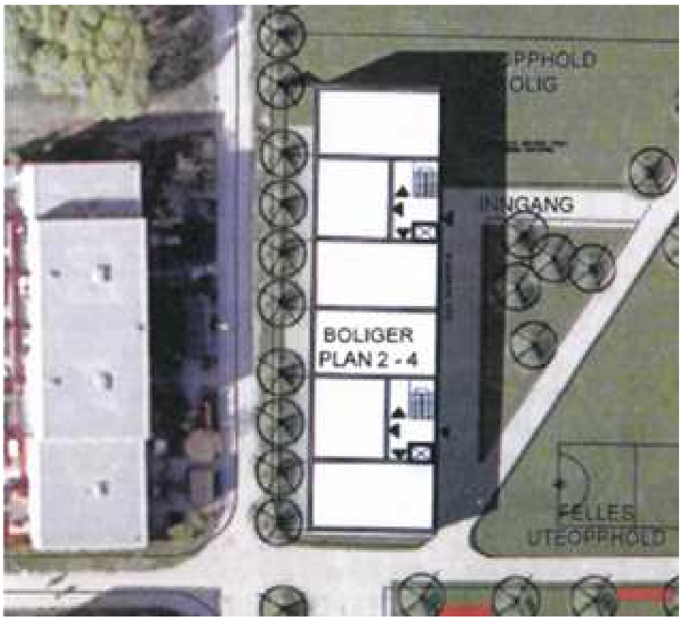

Figure 12: Apartments north

Each apartment offers a living space of 60-80 m^2. The facade consist of 20 % windows and 41 m^2 entrance doors as well as doors to balcony and terrace. The ground floor is connected with the soil. More details of the apartment building are shown in the Table 2.

Table 2: Apartments north

Apartments north

Effective area (BRA)	1,620 m^2	6 Apartments
Facade area	1,173.6 m^2	Thereof 41 m^2 doors
Window area	20%	142 windows (each 1.60 m x 1.20 m)
Heating volume	4,212 m^3	
Number of floors	3	Floor level: 2.6 m
Roof	540 m^2	Flat roof
Ground	540 m^2	Ground floor to soil

3.2.3 Assisted accommodations

The assisted accommodations are located in the southwest of the area and is shown in Figure 13. The building is connected to the existing Risvollan Center in the west and to Blaklivegen in the south.

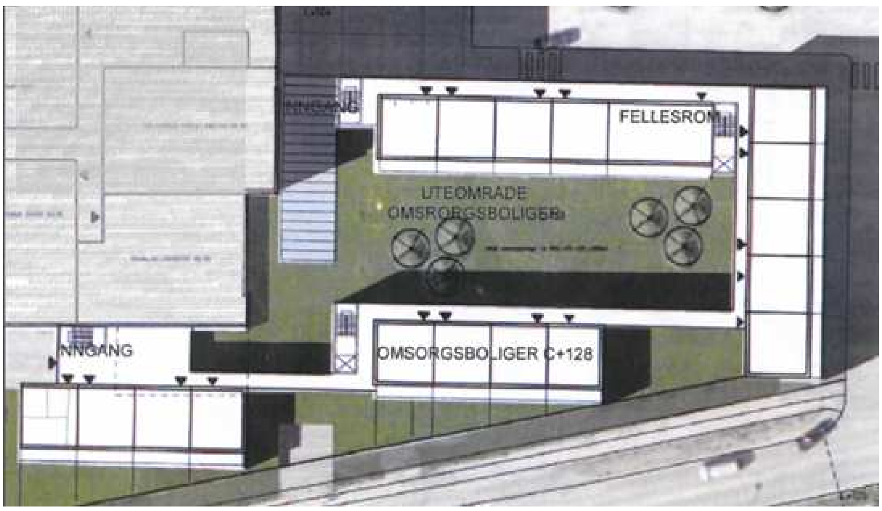

Figure 13: Assisted accommodations

The building has three floors with 51 accommodations. Each accommodation have two rooms with a total effective area of 55 m^2 living space. Additionally there is a common room at each floor. The whole building is connected with an air-conditioned corridor. The corridors facade consist of 60 % windows. The other facades cover 20 % windows and 147.5 m^2 entrance doors as well as doors to balcony and terrace. The building can also be reached from the underground parking by an elevator or staircase. All further available details are listed in Table 3.

Table 3: Assisted accommodations

Assisted accommodations		
Effective area (BRA)	4,710 m^2	51 Apartments
Facade area	3904.4 m^2	Thereof 147.5 m^2 doors
Window area	20%/60%	Corridor 60%, 934 windows (each 1.60 m x 1.20 m)
Heating volume	12,246 m^3	
Number of floors	3	Floor level: 2.6 m
Roof	1,570 m^2	Flat roof
Ground	1,570 m^2	Ground floor to underground parking

3.2.4 Care home

The care home is located in southeast of the Risvollan project area. The building is accessible through the main entrance in the first floor but also from the second floor. The bedroom floors are from the second up to the firth floor. The whole care home is with three departments on each floor organized. Each department has eight rooms. All floors are identical. All together, there are 72 bedrooms. The care home is shown in Figure 14.

Figure 14: Care home

Each floor of the three departments are connected with a common room. The useful area of the care center is 5,670 m^2. The facade is covered with 20 % windows and additional 40 m^2 doors. The first floor is accessible from the underground parking, which is connected with the parking of the Risvollan center and covers 1,080 m^2 of the ground floor of the building. The other 900 m^2 of the buildings underground is connected to the soil. Further details are listed in Table 4.

Table 4: Care home

Care home		
Effective area (BRA)	5,670 m^2	72 rooms
Facade area	2,121.6 m^2	thereof 40 m^2 doors
Window area	20%	284 windows (each 1.60 m x 1.20 m)
Heating volume	14,742 m^3	
Number of floors	4	Floor level: 2.6 m, first floor: reception
Roof	1,890 m^2	Flat roof
Ground	1,980 m^2	900 m^2 Ground floor to soil 1,080 m^2 Ground floor to underground parking

3.2.5 Healthcare floor and shopping floor

The already existing Risvollan center is located in the south of the area and is shown in Figure 15. The first floor is assigned as shopping floor and the second as healthcare floor with different healthcare possibilities.

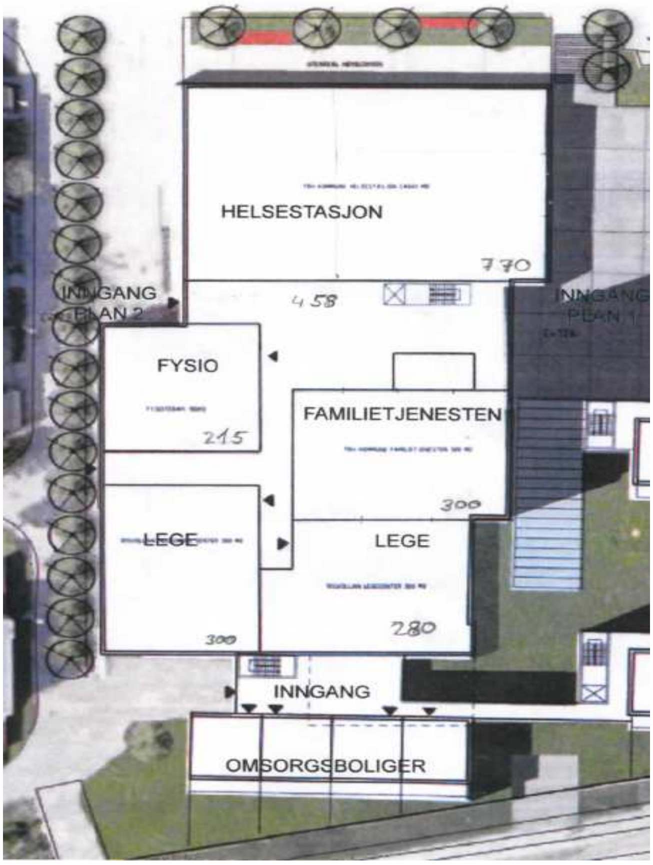

Figure 15: Healthcare floor and shopping floor

The ground is sloping at this part of the areal so that there is an entrance from the west to the second floor and another one from the east to the first floor. The south of the building is connected to the assisted accommodations. The western facade of the first floor is connected to the soil because of the sloping terrain. The rest of the facade is covered by 20 % of windows and additional 15 m^2 of doors. All further details of the building are shown in Table 5.

Table 5: Healthcare floor and shopping floor

Healthcare floor and shopping floor		
Effective area (BRA)	4,736 m^2	2 floors
Facade area	1,286.4 m^2	Thereof 15 m^2 doors and 321.6 m^2 contact to soil
Window area	20%	964.8 m^2 with 114 windows (each 1.60 m x 1.20 m)
Heating volume	14,208 m^3	
Number of floors	2	Floor level: 2.6 m, first floor shopping, second floor health care
Roof	2,000 m^2	Flat roof, 368 m^2 contact to apartments tower
Ground	1,980 m^2	Ground floor to soil

3.3 Solar irradiation

During a year, the intensity of the sun as well as the hours of sunlight varies. As Norway is located up north at the globe, there is a considerable difference between sunshine hours in winter and summer. In Trondheim is the time between sunrise and sunset at the maximum in June of 20h 48min and at the minimum of 4h 39min in December as shown in Figure 16.

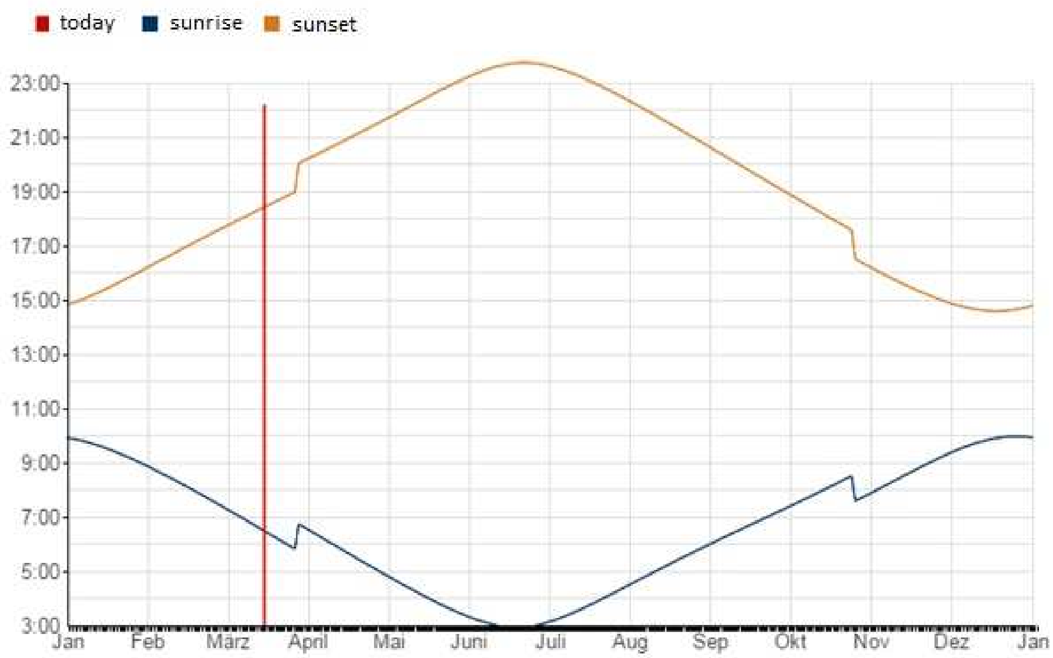

Figure 16: Sunset and sunrise of Trondheim during the year (www.sunrisesunset.de 2015)

The solar energy service www.SoDa-is.com provides the monthly sum of irradiation (I_{month}) in Trondheim (Figure 17). These data are used for the calculation in chapter 4.4 for the yield of the solar heat in the Risvollan area.

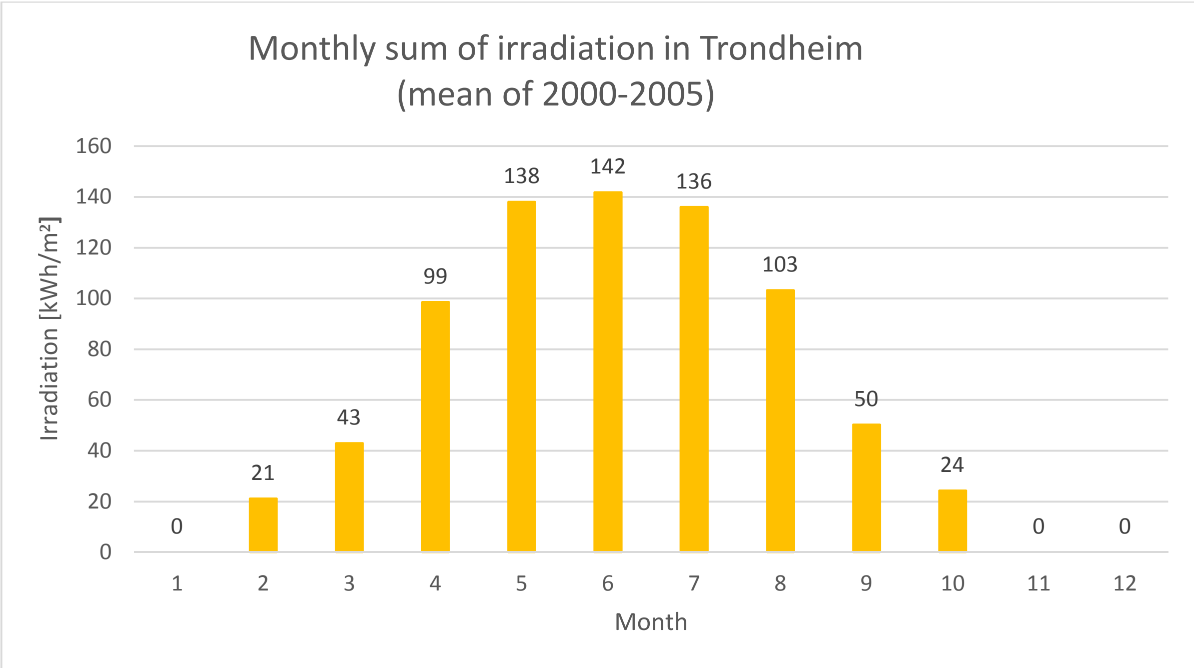

Figure 17: Monthly sum of irradiation in Trondheim (www.SoDa-is.com 2015)

4 Energy analysis of the Risvollan project area

The software SIMIEN is used to simulate the energy demand, the effective use and the room climate inside the planned buildings of the Risvollan project area. SIMIEN is a Norwegian Software from the company “ProgramByggerne”. The Software is used for evaluation of building regulations, identification of energy sources, calculation of energy demand, validation of the inside climate and dimensioning of the heating system, ventilation system and air-condition. (Dokka 2014)

The TEK 15 with the new technical building regulation is expected in 2015. The new version includes regulations to reduce the energy demand of new-planed buildings. The TEK 15 shall include values for ventilation, heating and construction material properties close to the NS 3701 Passive House Standard.

The values of the Norwegian Passive House Standard NS 3701 and the Standard NS 3031 for calculating the energy performance of buildings are used as database for the SIMIEN simulations in this chapter. Input data for the SIMIEN simulation like U-values, necessary quantity of air, values for thermal bridges, air leakage rate (n_{50}), SFP-Factor, heat input of lighting, technical equipment and persons and operation times are taken from NS 3701. The values for calculating the energy demand for heating the domestic hot water and the set point temperatures inside and outside the opening and operational hours of the buildings are taken from NS 3031.

The heat and cold demand is covered by direct and indirect energy sources. Direct energy sources is for example a geothermal energy system with heat pumps, sun-collectors or ice storage system. Internal loads from the use of lightning, electrical equipment and persons who stay inside the building are indirect energy sources. The buildings internal heat exchangers are radiators and there are additional heat exchangers placed in the ventilation system of the building. In case of the need for cooling the buildings, there is another heat exchanger located in the ventilation system for cooling.

Results of the SIMIEN simulations for the building of the Risvollan project area are depicted with Microsoft Office Excel. The original data sheets from the results of the SIMIEN simulation f each building are shown in Appendix A

4.1 Heat profile

4.1.1 Annual Heating demand

The heat demand of all buildings varies during the season. During the winter months, there is a generally higher heat supply required than in the summer months. By comparison all buildings of the Risvollan project area, the assisted accommodations show the highest heat requirement during the winter season.

Figure 18 shows the monthly heat demand of every building during a year. The main heat consumers especially between October and April, cause of the lower outdoor temperatures, are the assisted accommodations, the care home and the healthcare floor of the Risvollan Center.

At every floor of the assisted accommodation, the rooms are connected with a heated corridor whose facade have a huge window area. Standard external walls would provide better heat insulation than a facade of windows, but will not give the same lighting conditions.

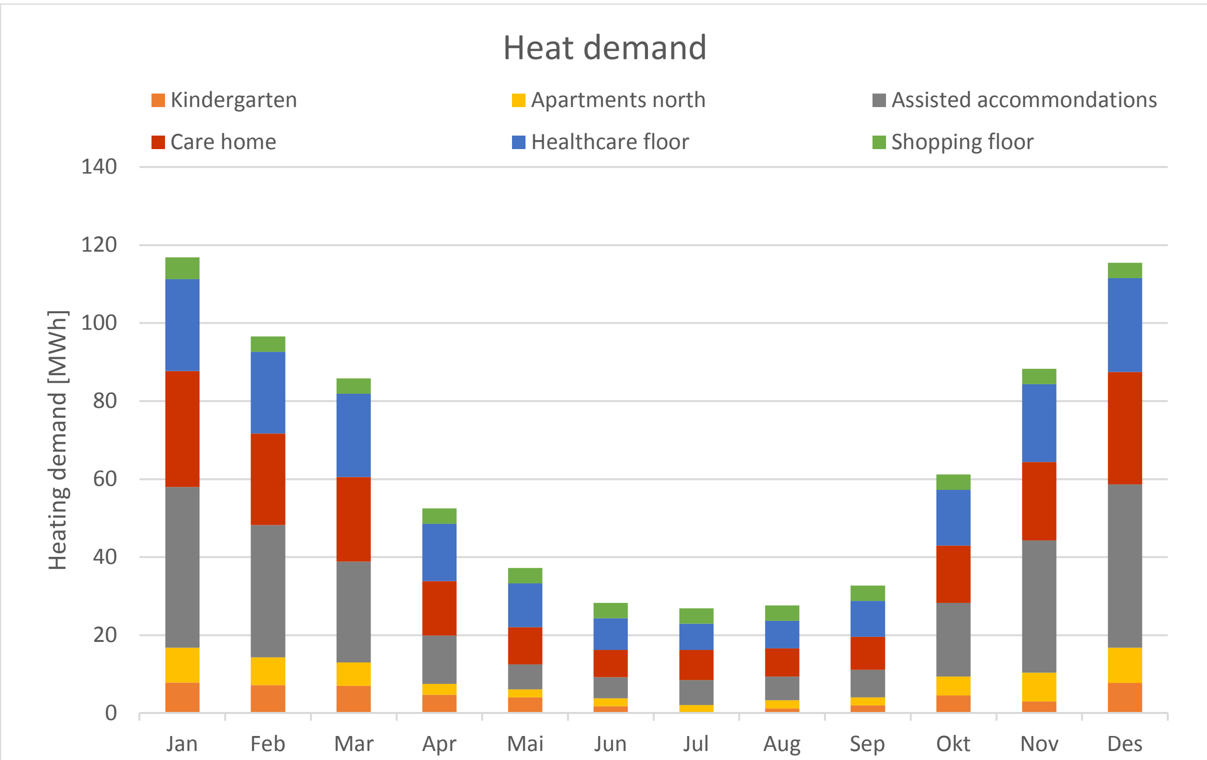

Figure 18: The heating demand of the Risvollan project area

For SIMIEN taken values for the electrical equipment of the shopping floor differ from the generally given data from NS 3701. The reason is that reports and studies like these from Trond Ivan Bøhn (2011), Langseth (2014) and also internal experience from SINTEF have shown that shopping centers have a higher energy demand than the given values by NS 3701. Experience of SINTEF has also shown that the internal loads by electrical utilities in a shopping center cover the required heating demand during winter.

Under consideration of this information, the values for internal loads are increased to 25 W/m^2 for lighting and 55 W/m^2 for technical equipment instead of the given 15 W/m^2 and 1 W/m^2 from NS 3031. The direct heat load of the shopping floor is after these corrections nearly constant over the year. The higher internal loads by electrical utilities are led that the heat supply with radiators and ventilation heat exchanger is smaller than 1 MWh/a. The entire heat demand of the shopping floor shown in

Figure 18 between the month February and December is required for the production of DHW.

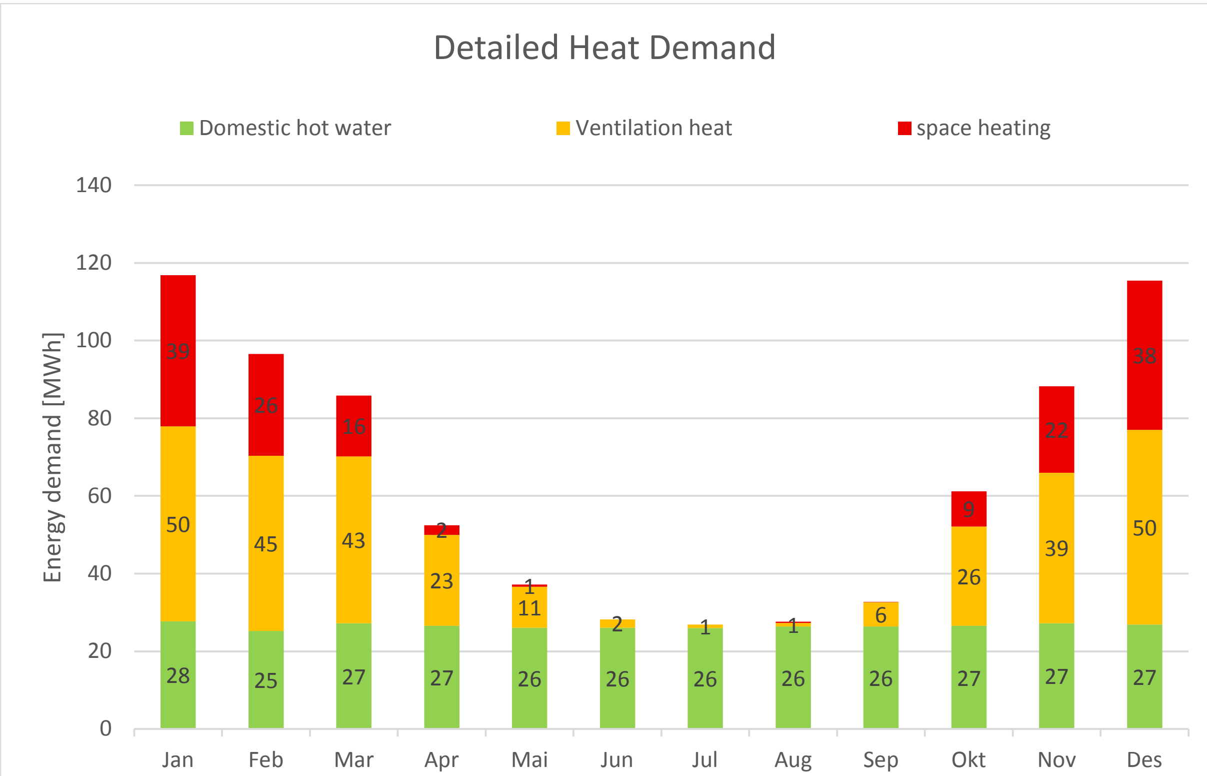

Figure 19: The detailed heat requirements

shows the detailed monthly heat demand of DHW, heat demand of ventilation system and space heating of all buildings in the Risvollan project area. The heat load required for the DHW production is nearly constant during the year and varies between 25 and 28 MWh monthly. The heat demand used for space heating and heating by the ventilation system varies strongly each month and depends on the prevailing outdoor temperature. During December and January the total heat demand is the highest with 117 MWh in December and 115 MWh in January. The yearly heat demand for space heating from ventilation and radiators and the supply of hot water for all buildings of the Risvollan project area is 769 MWh.

4.1.2 Specific Heating Demand

A special winter simulation with SIMIEN shows the maximal heat demand during the coldest period of the year. As reference for the winter simulation, the coldest day of the last ten years is chosen which is the 13th of January 2014. The highest temperature at the 13th of January 2014 was - 8.2°C and the lowest was -16.4°C. The average temperature this day was - 10.6°C. The results of the simulation are shown in Table 6.

Table 6: Maximal heat effect during the coldest day of the last ten years

Winter	**BRA**	**Maximal heat effect**
	[m^2]	[kW]
Kindergarten	1,400	11
Appartments north	1,620	2
Assisted accommodations	4,710	42
Care home	5,670	47
Healthcare floor	2,368	71
Shopping floor	2,368	71
Total	**18,136**	**244**

At the peak of heating during the coldest period of winter is a heating system necessary, which covers a maximal heat effect of 244 kW, for providing all buildings with sufficient heat energy. The highest heating power is needed at the shopping and healthcare floor with 71 kW each floor. These two floors have high voluminous rooms without separation of indoor walls.

4.2 Cold profile

4.2.1 Annual cooling demand

In the high summer season from June to August, it is necessary to lower the room temperature for keeping a comfortable indoor climate. During all other months there is no need for cooling the inside climate of the buildings. Due to Figure 20 is the highest cooling load required in August, the warmest month of Trondheim. During this month, all buildings except the apartments in the north, depending on cooling down the indoor temperatures for reaching a comfortable room temperature like given in NS 3031.

The results of the SIMIEN simulation are shown in Figure 20. The cooling demand during the summer from the shopping floor in the building of the Risvollan center is the highest in comparison with the other buildings. The constantly working electrical equipment of the shopping floor delivers extra input heat during the month of summer. Cooling of the buildings during the summer season is important for preventing an increase of the temperatures above the comfortable indoor conditions. Currently, the shopping floor supplies itself with cooling energy and at the actual project status it is not given, that they will join the future energy concept.

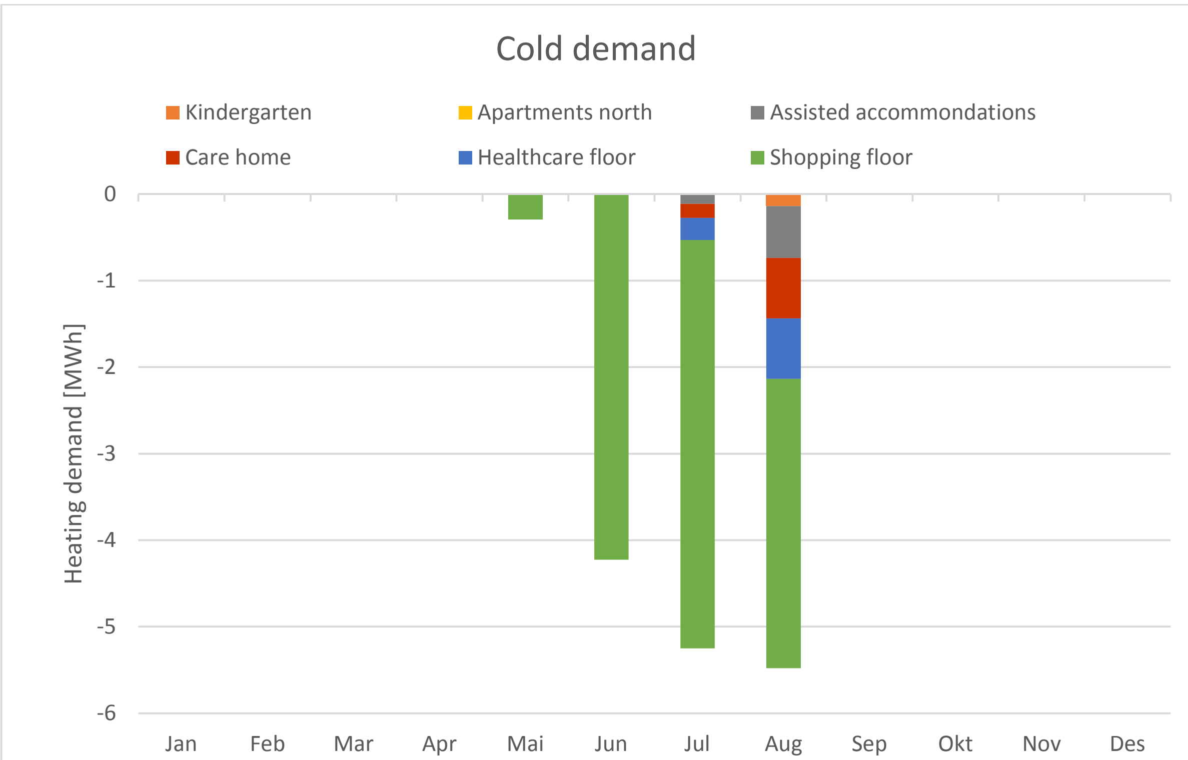

Figure 20: The cold demand of the Risvollan project area

All buildings together have a annual cooling demand of 15 MWh. There is no need of cooling for the apartments north during the whole summer season. All other buildings except of the shopping floor have an entire cold demand of 2.7 MWh during the two hottest month of the summer season.

Figure 21 shows that the entire cooling load of all buildings to the exclusion of the shopping floor is very small compared with the heating load. Cooling the indoor climate is just necessary during the two hottest month of the year, July and August.

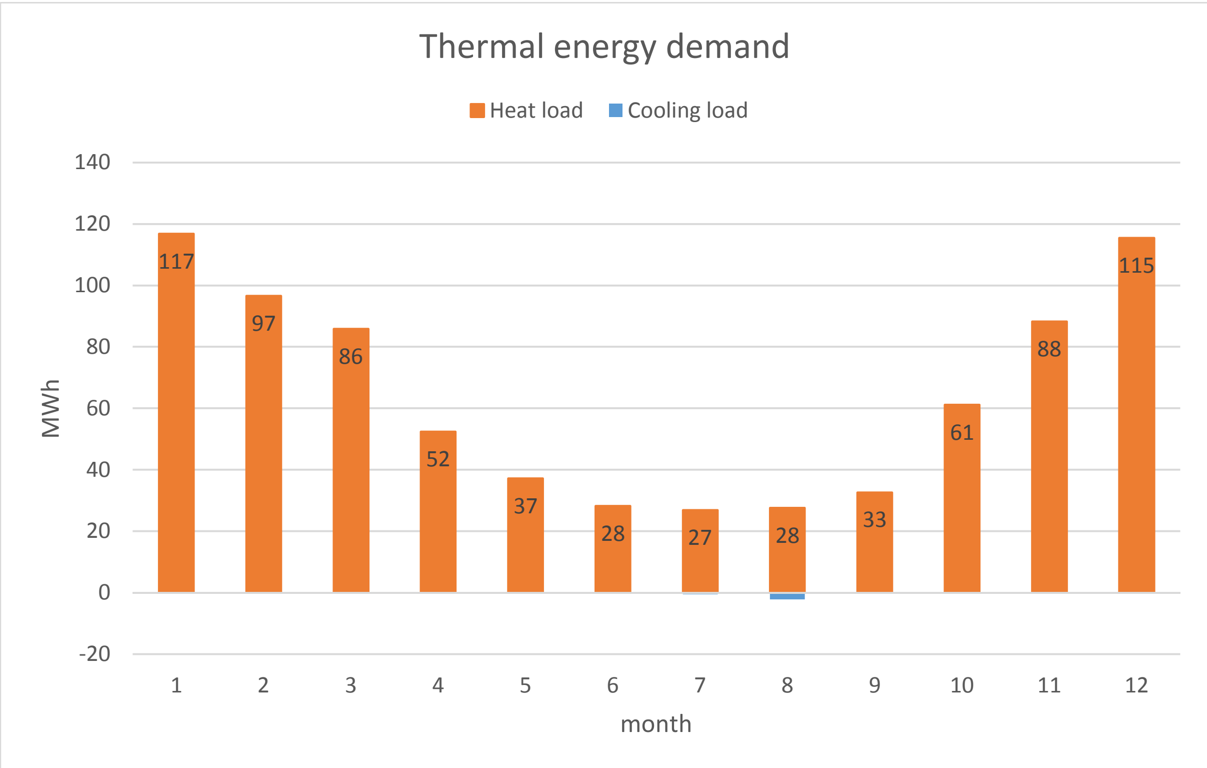

Figure 21: The total thermal energy demand of the Risvollan project area

4.2.2 Specific Cooling demand

As a reference for the SIMIEN summer simulation of the maximal cooling effect during the hottest period of the summer, the day with the highest temperature during the last ten years, 9th of July in 2014, is chosen. The 9th of July in 2014 had the highest temperature with 31.2°C. The minimum temperature at this day was 16.2°C and the average temperature reached 24.7°C. The results of the simulation for the maximal cooling effect are shown in Table 7.

Table 7: Maximal cold demand during the warmest day of the last 10 years

Summer	BRA	Maximal cooling effect
	[m²]	[kW]
Kindergarten	1,400	17
Appartments north	1,620	3
Assisted accommodations	4,710	45
Care home	5,670	54
Healthcare floor	2,368	71
Shopping floor	2,368	71
Total	**18,136**	**260**

The cooling system of the buildings at the Risvollan project area must be dimensioned for a maximal cooling effect of 260 kW, so that the comfortable indoor conditions, given from NS 3031, can be reached. The highest cooling effect is necessary at the shopping and healthcare floor because of the high amount of electrical devices inside the building. Excluding the shopping floor of the Risvollan Center the maximal cooling effect is 189 kW.

4.3 Electrical energy demand of the buildings

The electrical demand of the buildings comes from all used technical equipment, lighting, fans for the ventilation system, circulation pumps as well as the energy for running the heating pumps.

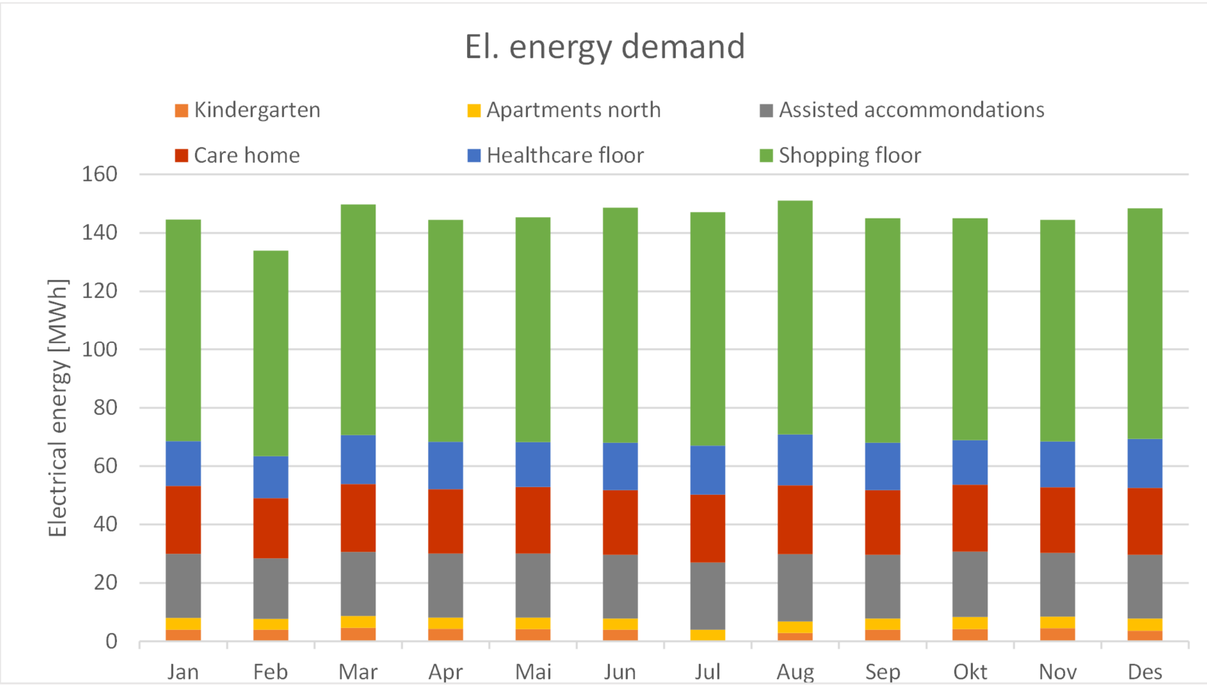

Figure 22: The electrical energy demand of the Risvollan project area

The entire electrical energy demand of all buildings is nearly constant during the year. The main part of the electrical demand of the Risvollan project area is needed for the shopping floor with all its technical utilities, for instance for cooling food.

Figure 23 shows that there is a nearly constant energy demand between 26 MWh and 29 MWh, which is used for the operation of the heat pumps. The electrical energy consumed of running the heat pumps is used in a later calculation to calculate the coefficient of performance, COP. The COP is the decisive coefficient to describe the efficiency of a heat pump system.

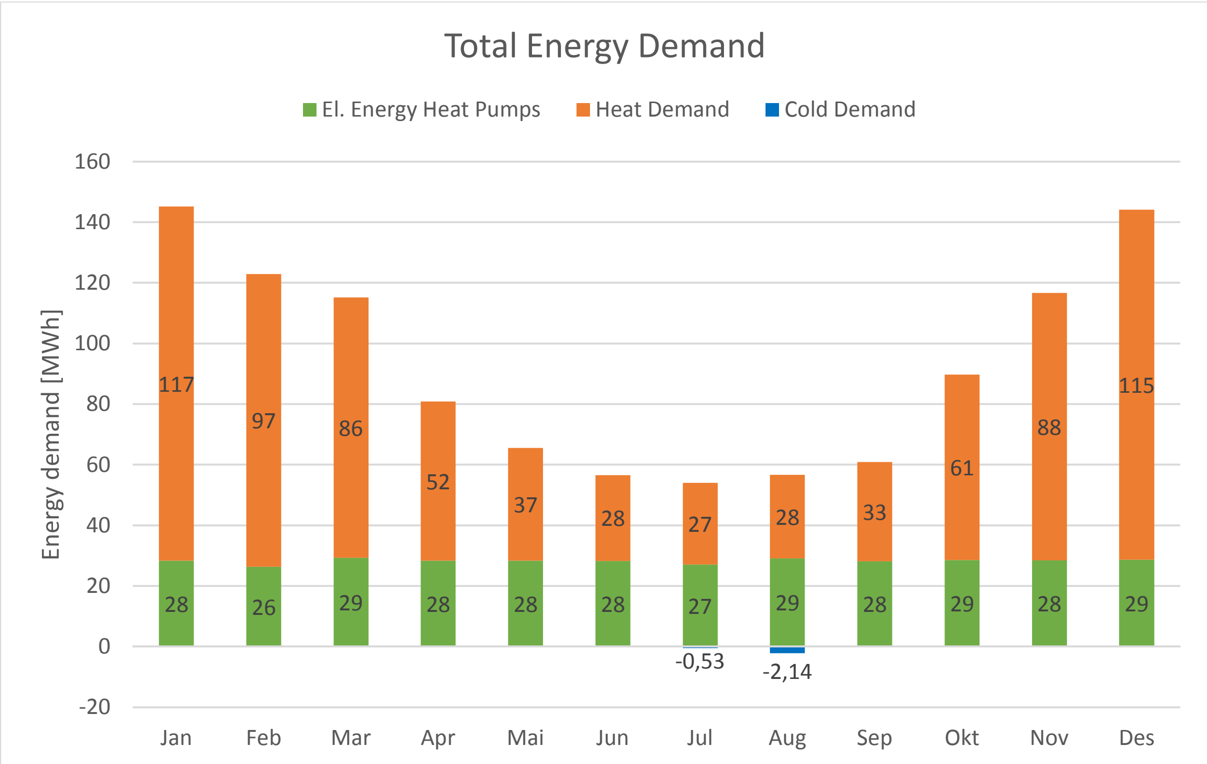

Figure 23: Total energy demand

4.4 Solar heat yield of the rooftop area

The rooftop of all buildings at the Risvollan project area are flat roofs. The entire roof area is 6,700 m^2. Pir II AS has worked out a proposal of the Risvollan project area with an illustration study. This study includes the shadow map of the Risvollan buildings, which shows the from shadows covered roof area during the path of the sun in 20th of June, 20th of March and 20th of September. The shadow map is shown in Figure 24.

Figure 24: Shadow map of the buildings at Risvollan project area

The existing Risvollan center tower covers the rooftop of the northern part of the Risvollan Center building with shadow during the sunny days from March to September. Parts of the assisted accommodation are unusable for the heat absorbers because of the shadow from the Risvollan Center tower. A detailed list of the usable rooftop area of the different buildings is shown in Table 8.

The not usable roof area extracted from the total roof area are usable for the installation of the heat absorbers. The not usable rooftop area is the from the shadow covered rooftop area during the sunniest days of the year. Additionally is an area of approximately 30 % of the usable rooftop area extracted because of the use for other devices and space for maintenance. The usable roof area is at least 4,185 m^2.

Table 8: Usable roof area for solar collectors of Risvollan buildings

	Roof area A_{roof} [m^2]	usable roof area for solar collectors $A_{roof, usable}$ [m^2]
Kindergarden	700	490
Appartments north	540	416
Assisted acommodations	1,570	1,099
Care home	1,890	1,323
Healthcare floor and shopping floor	2,000	857
Total	6,700	4,185

The efficiency of a heat absorber or solar collectors depends mainly on the installed kind of collector and the temperature difference between fluid and surrounding. The temperature difference for determining the efficiency factor is defined as the difference between middle fluid temperature and surrounding temperature. The Viessmann Company recommended heat absorber tubes for running an ice TES.

In a reference project in Oslo heat absorbers are used to recover a geothermal well grid. In this project archived the annual mean temperature difference between fluid und surrounding is approximately 30°C. If the solar heat is used for storing, for instance in an ice TES or used for recovering a geothermal well grid, than there is no need of using water temperatures higher than 60°C. For the assessment of the expected monthly solar yield of the rooftop area of the Risvollan buildings, a temperature difference of 30°C can be assumed. The efficiency factor is dimensioned with help of the diagram of DIN EN 12975, which is shown in Figure 25.

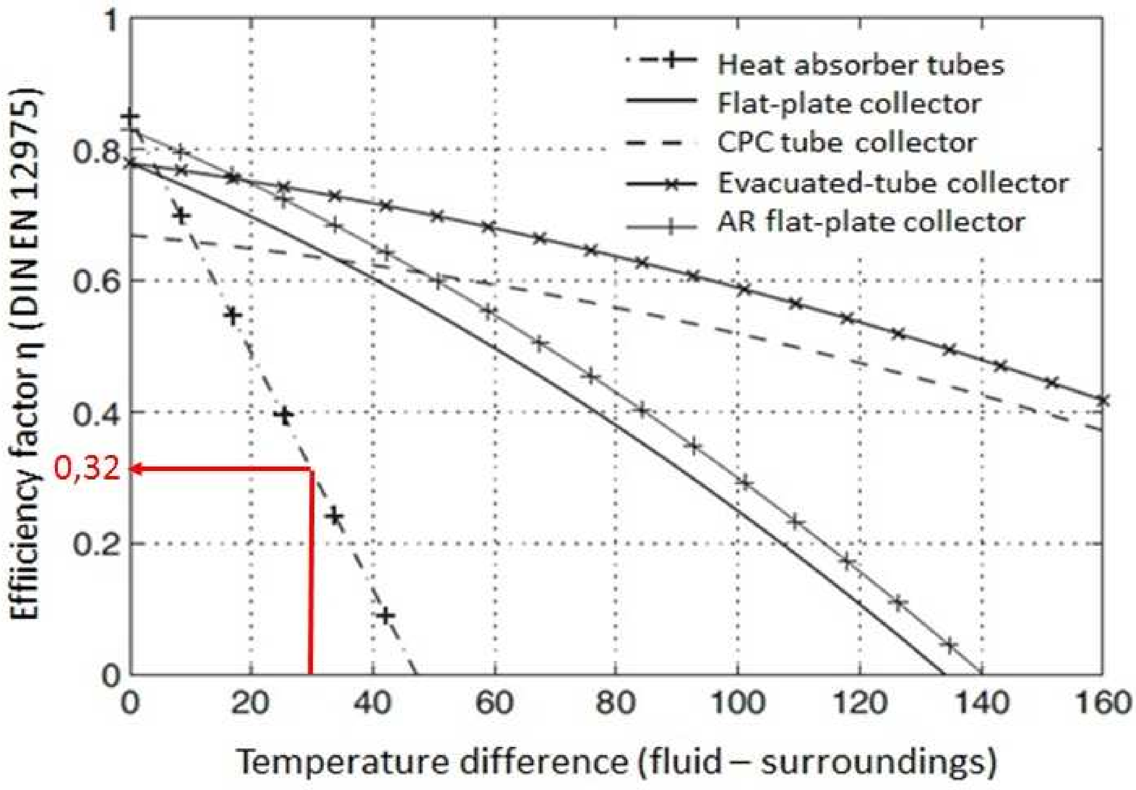

Figure 25: Efficiency factor of the heat absorber tubes

With the mean temperature difference of the reference project and the recommended heat absorber tubes, an efficiency factor (η) of 0.32 for solar heat absorbers can be reached.

For an assessment of the expected monthly solar yield ($\dot{Q}_{\mathrm{yield,monthly}}$) for the entire usable rooftop area ($A_{\mathrm{roof\,usable}}$) of the Risvollan project buildings, the following equation is used:

$$\dot{Q}_{\mathrm{yield,monthly}} = \eta * A_{\mathrm{roof\,usable}} * I_{\mathrm{monthly}}$$

The values from the monthly irradiation (I_{monthly})) come from Figure 17. The results of the monthly heat yield are shown in Figure 26. The expected annual produced solar heat load for the usable roof area of the heat absorbers is 1,013 MWh. The month with the highest solar yield is June with 190 MWh. A heat yield of 1,013 MWh/a means that each m^2 with heat absorber covered roof area produces approximately 242 KWh a year.

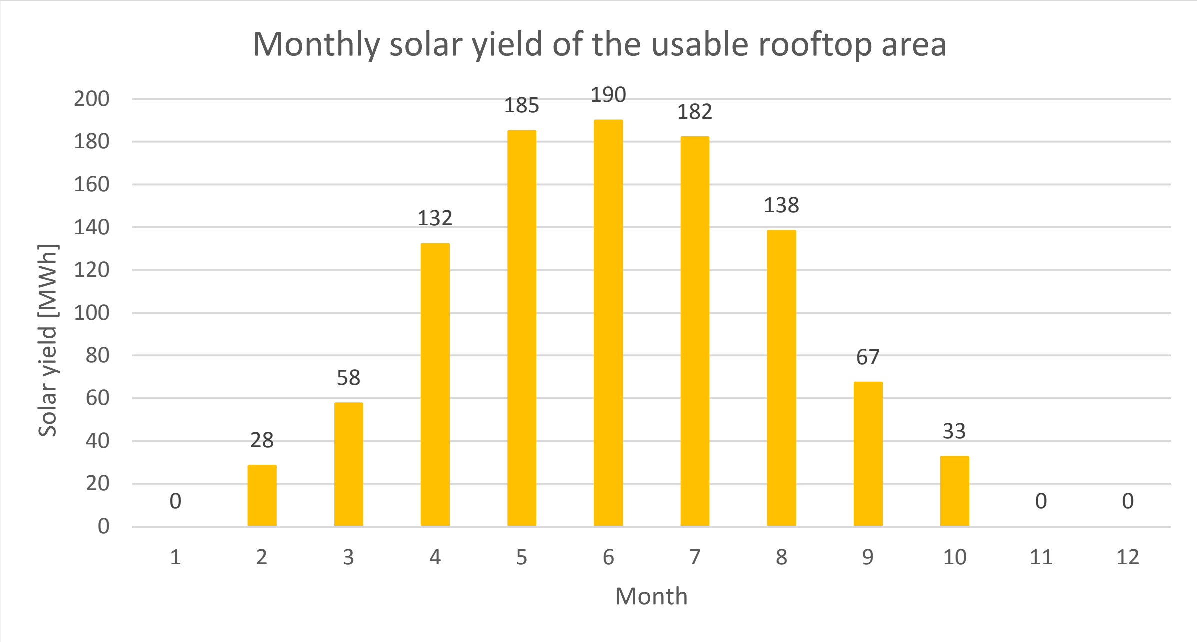

Figure 26: The monthly solar yield of the usable rooftop area

4.5 Thermal energy extraction of a geothermal well grid

For covering the heat and cold demand of the buildings in the Risvollan project area from geothermal wells, more than one BHE will be necessary. A dimensioning of a single borehole can be made with the recommended calculations of VDI 4640. For systems with more than one BHE, systems with more than 2400 h of annual operation duration, systems with additional heat sources/sinks and systems with an overall heat pump heating output > 30 kW there are other calculation models necessary. In case of a geothermal well grid, it is necessary to simulate the behavior of the underground temperatures during the planned lifetime. VDI 4640 recommended numerical simulations methods for an exact calculation of the necessary amount of geothermal wells and the behavior of the underground temperature in case of a planned geothermal well grid. Geothermal well grids are complex systems in which the BHE can influence each other or the groundwater flow can influence the heat yield. Numerical methods are also suitable for statements on the long-term behavior and for influencing the environment of borehole heat exchanger systems. (VDI 4640)

A method for dimensioning BHE with sufficient accuracy was developed by Claesson at the University of Calmers in Sweden. His method combined with a numerical simulation model are involved in the EED (Energy Earth Designer) program. The EED program is used for simulations of the underground temperature behavior of geothermal well grids. Monthly heat extraction rates and input energy for thermal recovering of the underground can be simulated. Thereby can be made settings about different local underground parameters as well as different system of BHE. As results are given out maximal and minimal fluid temperatures for every year of operation. The maximal operation time is limited to 25 years. With the results of the EED can be analyzed and evaluated the thermal underground behavior during longtime extraction. A harmful operation caused of faulty dimensioning can be prevented on that way.

The VDI 4640 gives recommendation about the behavior of the underground temperatures during seasonal extraction. Thereby should the temperature of the heat carrier fluid, which returns to the BHE's not exceed the limiting range of ± 11 K during base load operation in a weekly average compared to the undisturbed ground temperature. At peak loads, the temperature change should not exceed ± 17 K. (VDI 4640)

Further should the mean temperature of the fluid not sink to less than 0°C during the coldest month and base-load. Preferably, it should remain significantly above 0°C. This avoids ground freezing and ensures higher seasonal performance factors of the entire heating system. Also during peak-load should the fluid temperature not drop below 0°C on the coldest day over a 20-year lifetime. (Banks 2012)

The drilling depth is limited to 230 m because of the used equipment and the pressure limit from the compressors of the drilling companies, due to Randi Kalskin Ramstad from the department of Geology and Mineral Resources Engineering of NTNU. She also recommended that the minimum mean temperature in the BHE of the fluid during base load should not fall more than two degrees after 25 years of utilization. The undisturbed ground temperature in Trondheim is 7°C.

A BHE grid should be dimensioned, so that during heat extraction and even during the recovering process the geothermal wells and their surrounding do not thermal effect each other. A recommended minimum distance between the boreholes is after Ingrid Stober and Bucher (2014) 5 m to each other.

In case of the Risvollan project area have to be covered the heat demand of 769 MWh/a. The maximal depth for each geothermal well is 230 m. A dimensioning for a geothermal grid with a distance between the boreholes of 7 m and 60 wells is made with EED. Further frame conditions for the dimensioning are shown in Table 9.

Table 9: EED frame condition for a geothermal well grid with 60 boreholes

EED frame conditions	
Heat load	769 MWh/a
Heat recover load	0 MWh/a
SPF	3,5
Borehole depth	230 m
Number of Boreholes	60
Spacing between BHE	7 m
Formation of BHE field	5x12 boreholes/ 28 m x 77 m
Thermal conductivity of the underground	1,330 W/(m·K)
BHE-type	Single-U
Borhole diameter	140 mm

The behavior of the underground temperature like they are recommended in VDI 4640 can not be reached by the geothermal well grid with 60 boreholes and the conditions of Table 9. The Figure 27 shows that the base minimum fluid temperature (green line) falls under 0°C after 4 years of operation. The simulation reflected no acceptable conditions for the underground. Further simulations with a higher amount of boreholes are showing neither explicit improvement of the underground temperatures behavior. It can be assumed that in case of operating a geothermal well grid it will be inevitable to recover the geothermal borehole grid with solar heat for archiving a well-adjusted system.

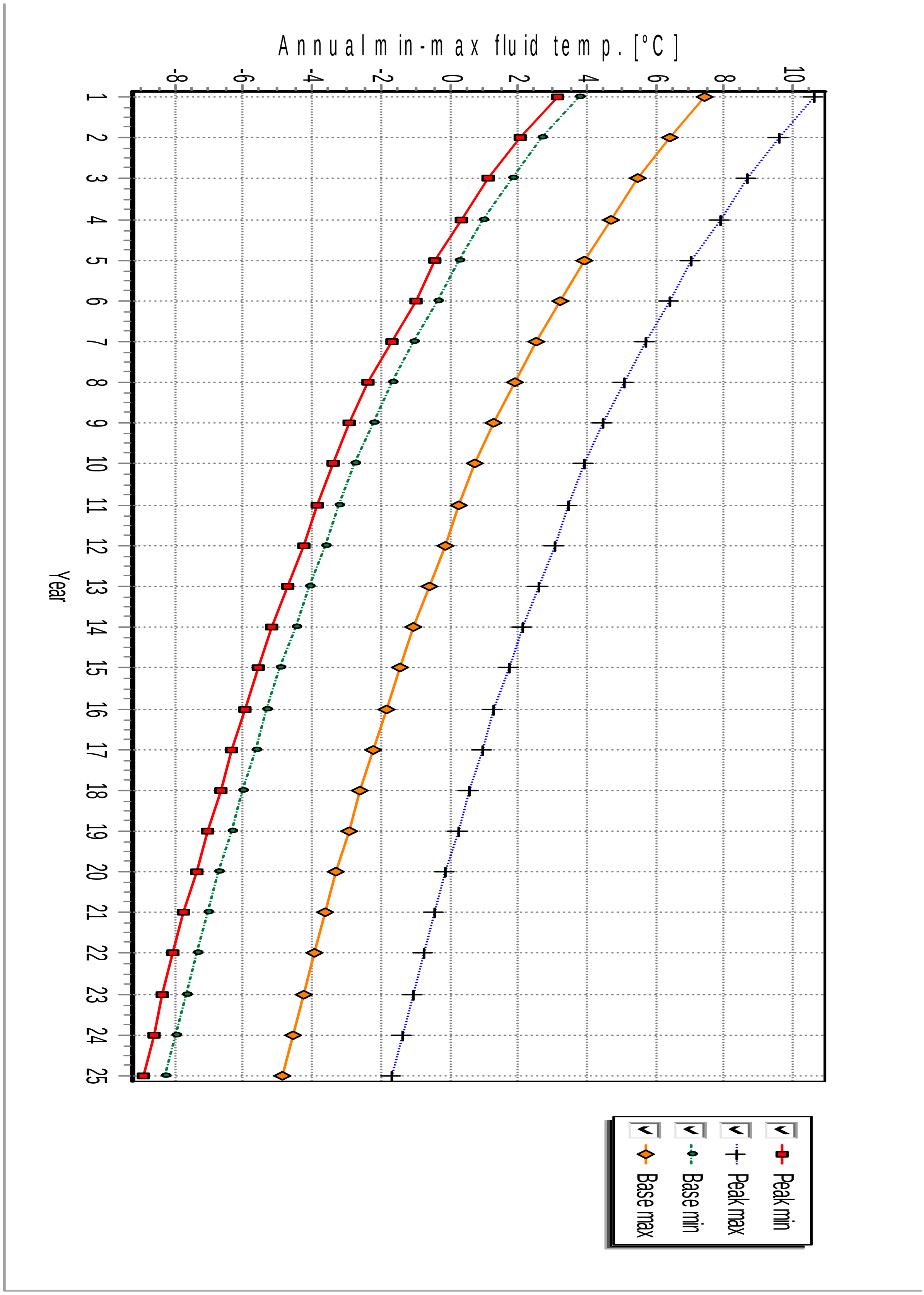

Figure 27: Annual fluid temperatures for a geothermal well grid with 60 boreholes

5 Concepts for thermal energy supply

The challenge of the following introduced energy system is to meet the building requirements for heating and cooling in the Risvollan project area. This chapter includes the considered technologies from the previous chapter to use thermal energy sources and to store the energy. The considered technologies are solar collectors, geothermal wells, ice TES and district heating. Three different energy systems are designed and their application for covering the thermal energy demand of the buildings is discussed. All system variants use different available energy sources for covering the thermal energy demand. The technical consideration of raising the available temperature level through heat pumps to the operations temperatures is not included. For an estimation of the need of external energy, predictions about the expectable SFP, COP, SEER and EER for the different systems there are made leant on literary recommendations and case studies.

5.1 Energy concept 1: solar collectors and geothermal wells

The system components of energy concept 1 are solar heat absorbers on top of the buildings and a geothermal well grid. The combination of solar heat and geothermal boreholes leads to notable synergies. Both can function as heat sources and the geothermal wells as TES as well. The part-systems are connected and they interact with each other. Figure 28 shows the principle of energy concept 1.

During the summer, when the heat is required just for covering the domestic hot water demand, all the produced excess solar heat is used to recover and store heat in the boreholes. When extracting heat energy from the underground during the winter season, the underground temperature decreases ongoing. During summer, the produced heat energy of the solar collectors is lead into the BHE, so that the temperature in the ground regenerates faster.

During storing of surplus heat, the normal underground temperature increases over the undisturbed underground temperature. After summer season, the heat pump will have good start conditions for heating. The number of necessary geothermal wells can be reduced if the underground is used as TES as well. The combination of both part-systems increases the COP of the heat pumps during winter season and accordingly the SPF of the entire system. In case the input temperature of the fluid inside the BHE reaches a temperature higher than 30°C, the material of the BHE must be considered to prevent damages (Stober, Bucher 2014).

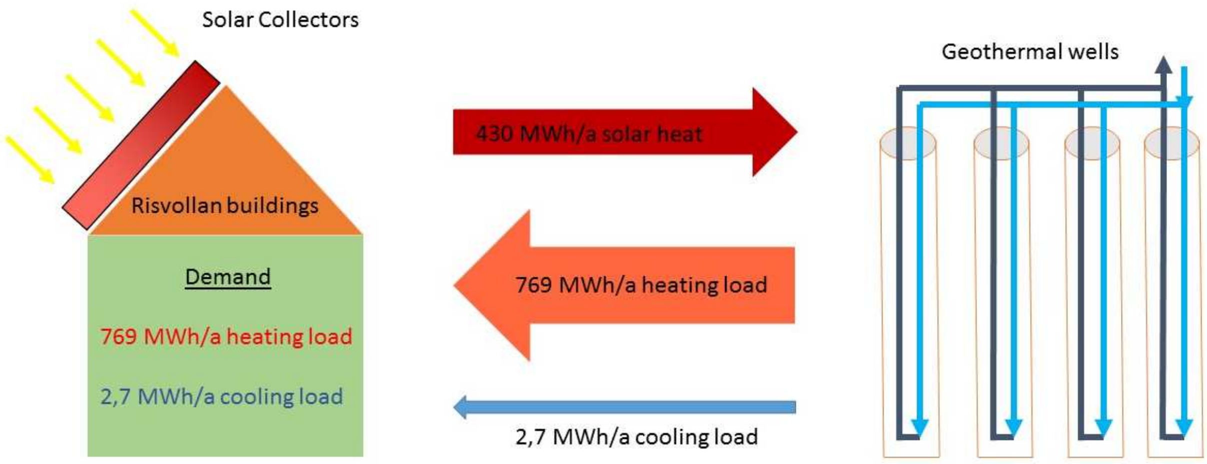

Figure 28: Energy concept 1 - solar heat and geothermal wells

A further synergetic effect is reached if the BHE's are used to cool down the buildings during the summer period as well. The cooling load of the Risvollan buildings is highest during the hottest months, July and August. Hence the underground is cooled down after the winter period through heat extraction from the BHE, the cold underground temperatures can now be used to cool down the buildings. A sufficient supply of cooling energy is also possible while the underground regenerates with solar heat. For cooling, it is preferable to use "free cooling" mode instead of "active cooling" mode. The "free-cooling" mode is advantageously for the SEER of the system, hence there is no operation of the heat pumps. During cooling peaks on the hottest days of the year, the heat pumps can also be used for "active cooling" but this should be avoided. A reference project at the University of Ontario Institute reached an EER between 16.7 and 17.9 during cooling mode with cold energy from the underground. (Dinçer, Rosen 2011).

A simulation of the energy concept 1 for covering the heat demand, like shown in chapter 4.1 Figure 19, is made by EED for dimensioning the geothermal well grid. The frame conditions for the dimensioning are shown in Table 10. The BHE grid is dimensioned to reach a heat energy output of 769 MWh/a and a recovering heat load from the heat absorbers of 430 MWh/a. An expected SPF of 3.5 means that 550 MWh/a are covered by the BHE grid and 219 MWh/a comes from external electrical energy during operating the heat pumps. The annual heat load of 430 MWh for thermal recovering of the underground is empirically based with EED and shows a stable underground temperature trend like it is shown in Figure 29. The specific factor of 242 kWh/m^2 for dimensioning the heat absorbers area on the rooftop, as calculated in chapter 4.3, shows that a rooftop area of approximately 1,776 m^2 is sufficient for delivering the geothermal wells with 430 MWh/a heat energy for recovering during summertime.

Table 10: Frame conditions for EED of energy concept 1

EED frame conditions	
Heat load	769 MWh/a
Heat recover load	430 MWh/a
SPF	3,5
Borehole depth	230 m
Number of Boreholes	48
Spacing between BHE	7 m
Formation of BHE field	6x8 boreholes/ 35 m x 49 m
Thermal conductivity of the underground	1,330 W/(m·K)
BHE-type	Single-U
Borhole diameter	140 mm

The undisturbed underground temperature is 7°C in the entire area of Trondheim (EED). That means that the max mean fluid temperature should not reach higher temperatures than 18°C, as recommended in VDI 4640 and discussed in chapter 4.5. The minimum fluid temperature should not fall under 0°C. Preferable is a few degrees higher temperature than 0°C of the circulating fluid.

The annual maximum and minimum fluid temperatures of the mean base load during the simulation are shown in Figure 29. The maximum base temperature is the highest annual reached temperature of the fluid and is reached annually at July during recovering the underground with solar heat. The maximum mean base temperature is 16.1°C and accordingly 1.9°C under the recommended highest mean temperature.

The minimum mean base temperature is noted at the end of each month and the lowest in the end of January every year when the heat extraction from the underground is at the highest stage. The minimum mean base temperature of 3.4°C is adequately high for preventing damages on the system and after the first 3 years of extraction at a constant level. The peak minimum temperature in Figure 29 shows the annually reached minimum temperature which is noted at the end of each month while peak heat extraction took place. According to the simulations the peak minimum temperature does not fall under 0°C during the lifetime of 25 years. During the first 3 years of operation, a decrease of the minimum mean base temperature is notable but a critical undercut of 2°C can be prevented.

The simulation has shown that with taking the frame conditions from chapter 4.5 into consideration, a geothermal well grid with 48 BHE is sufficient to supply the buildings with thermal energy during summer and winter season. The simulation has been carried out with a formation of the 48 BHE in a 6 x 8 rectangle of the boreholes and a distance of about 7 m between each other. Depending on the available area for the BHE grid, it can be advantageous to choose more effective grid formations like a 4 x 12 formation, which means less thermal influence between the boreholes.

The complete results of the EED simulation for the geothermal well grid of energy concept 1 are attached in Appendix B.

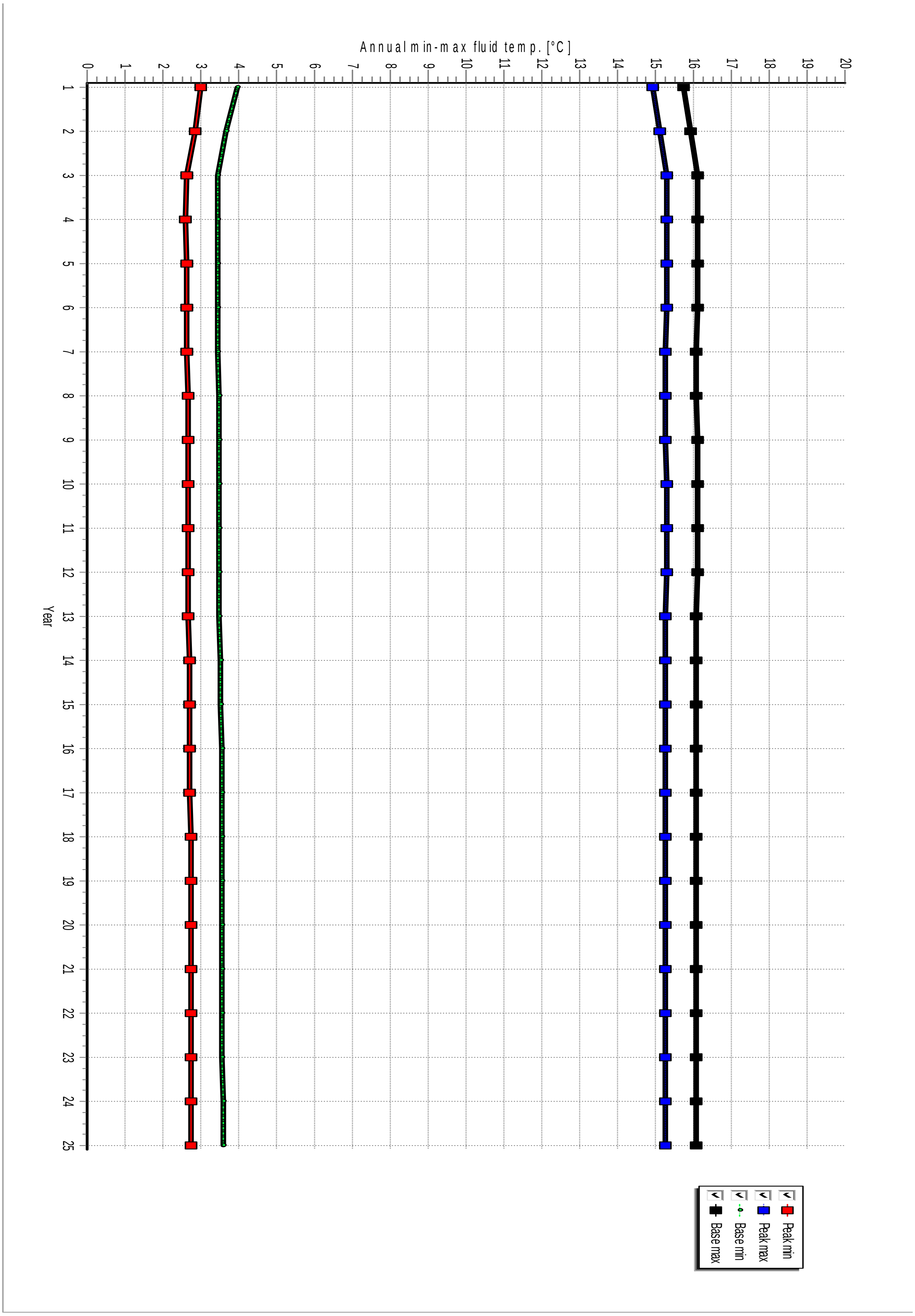

Figure 29: Minimum and maximum fluid temperatures

5.2 Energy concept 2: seasonal ice TES and solar heat

The second concept consists of an ice TES used as seasonal storage system for covering heating and cooling demand of the buildings. The water filled storage tank is used for storing thermal energy during the summer and warmer months of the year. Special air/water absorbers are used for generating heat energy during warm days also without direct sun irradiation. The air/water absorbers are used for producing domestic hot water during warm season and for regenerating the Ice TES during warmer days as well. The necessary cooling load of 2.7 MWh/a demanded of the buildings during summer can be covered of the surplus cold. The surplus cold energy is produced during the winter season while heat energy is extracted and is a byproduct during summer season while recovering the entire system. The systems most advantageously operating mode for cooling the buildings is the free cooling mode. The cold fluid from the tank is led without passing the heat pumps straight to the heat exchangers. The free cooling mode increases the SEER of the entire system. The principle of the energy concept can be seen in Figure 30

While the heat demand increase immediately at the beginning of the winter season, the heat energy is extracted from the ice TES and transformed with the help of heat pumps to a higher temperature level. The highest stored energy amount in the ice TES can be extracted during the phase change from water to ice while the temperature stays constantly at 0°C.

The dimensioning of the ice TES depends on a number of environmental parameters and is best done on the basis of previous experience. After consultation with Matthias Rauch from the German company Viessmann recommended a tank size of 1,500-1,800 m^3 for the calculated thermal energy demand of the planned buildings in the project area. The dimension of a 1,800 m^3 tank is recommended with 24 m in diameter and 4 m height (Matthias Rauch from VIESSMANN 2/14/2015).

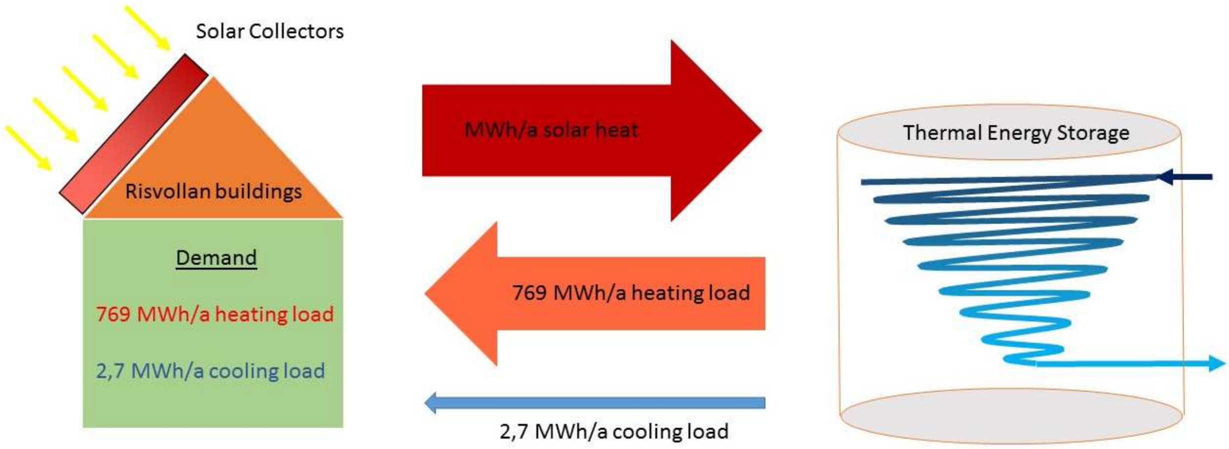

Figure 30: Energy concept 2 - Ice TES and solar heat

As a minimum the air/water absorber have to produce the yearly heat demand of the buildings. This energy must be partly stored in the TES and partly used for direct heating or producing domestic hot water. The heat energy stored in the ice TES during summer season must exceed the heat energy demand of the buildings in winter season. This is less than 75 % in most cases because of the energy storage factor for seasonal application (Dinçer, Rosen 2011) in the most cases. A reference project in Friedrichshafen reached a storage efficiency of 60°% (Rezaie et al. 2015). It seems to be possible that the entire available roof area of 4,185 m^2 is exploited for the air/water collectors. Viessmann provides a special double collector, which means reduced demand of rooftop area.

An intelligent heat source management is indispensable. The heat pumps are always supplied by the heat source with the best operating conditions. Whenever there is a heat potential of the air/water absorbers available it must be used to melt the ice in the storage tank. With a good adjusted energy management of the system a SPF from 4.2 to 4.6 is possible. (Wolfgang Schmid 2013)

Ice TES in this size are normally build from concrete which is the most economically material. Costs can also be reduced through integration of an ice TES in the foundation of buildings (Dinçer, Rosen 2011). Large-scale and long-term thermal storage is typically more cost effective than small-scale TES (Rezaie et al. 2015).

5.3 Energy concept 3: district heating and seasonal ice TES

The district heating system of Trondheim is operated by Statkraft Varme. In the scenario of energy concept 3, the Risvollan area is connected to the district heating grid. The entire heat demand for the buildings in the project area is covered from the heat energy from this grid. Statkraft Varme delivers the heat energy to a heat exchanger in the area. From here, the building owners and operators are responsible for the further distribution. The principle of concept 3 is shown in Figure 31.

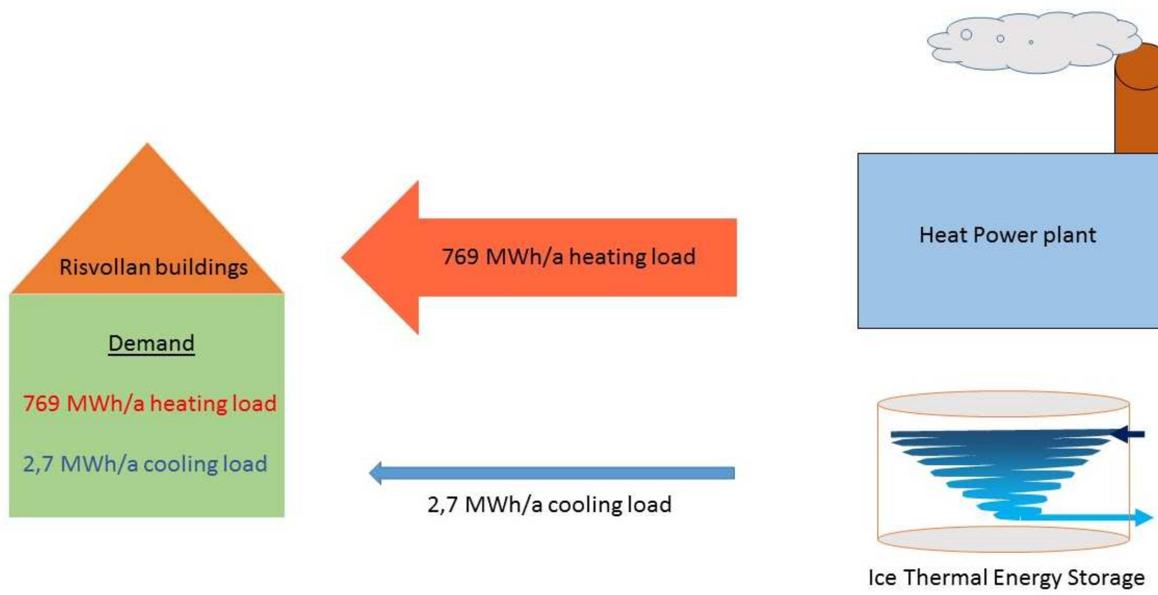

Figure 31: Energy concept 3 - district heating and ice TES

Additionally there is an ice TES used to cover the demand of 2.7 MWh/a of the buildings during the summer season. During the winter season, the water inside the ice TES is transformed into ice. During cold days with ambient temperatures below 0°C, the fluid circulating inside the air/heat absorber and ice TES is cooled under 0°C from the absorbers. The cooled fluid, which comes from the absorbers, is led through the coil in the Ice TES. The water inside the ice TES freezes and the cold energy is stored until summer when it can be used for cooling the buildings. The free cooling mode has also in this scenario a positive effect on the SEER of the system. It can be assumed that during the free cooling mode, an equal EER like it is mentioned in chapter 5.1 of about 16.7 to 17.9 can be reached.

A storage efficiency lower than 75 % is a common factor for this kind of storage system (Dinçer, Rosen 2011). Operating temperatures of the ice TES between -2°C and 15°C are recommended according to Dinçer and Rosen 2011. The thermal energy storage medium is water. Following equations provide information about the expected dimension of the ice TES for cooling tasks:

$$-2°C_{ice} \underset{4{,}2\ \mathrm{kJ/kg}}{\Longleftrightarrow} 0°C_{ice}$$

$$0°C_{ice} \underset{334{,}4\ \mathrm{kJ/kg}}{\Longleftrightarrow} 0°C_{water}$$

$$0°C_{water} \underset{63\ \mathrm{kJ/kg}}{\Longleftrightarrow} 15°C_{water}$$

The heat capacity of water, as it is used for the calculation, is 4.2 kJ/ (kg·K) for the temperatures between 0°C and 15°C. The heat capacity of ice between -2°C to 0°C is 2.1 kJ/ (kg·K). From this follows that the transforming energy for 1 kg ice at 0°C to 0°C water is 334.4 kJ. The storable energy for a kg of water ($c_p \cdot \Delta T$) in between the operation temperature of - 2°C to 15°C is 401.6 kJ. The size of an ice TES with a storage capacity of 2.7 MWh/a (9,720,000 kJ) for the cold supply during summer can be calculated as follows:

$$V = \frac{Q}{\rho \cdot c_p \cdot \Delta T}$$

$$V = \frac{9{,}720{,}000\ kJ}{918\ {}^{kg_{ice}}/_{m^3} \cdot 401.6\ {}^{kJ}/_{kg}} = 26.37 m^3$$

The storage efficiency depends on insulation and the surrounding conditions. With a common storage factor for seasonal application less than 75 % and a proven storage efficiency of 60°% in reference project (Rezaie et al. 2015) the storage factor of this project is estimated to 65 %. A higher storage size is hence needed for covering the required cold demand:

$$V_{incl.\ losses} = \frac{26.37 m^3}{65\%} \cdot 100\% = 40.6\ m^3$$

Accordingly for covering the annual cold demand of 2.7 MWh an ice TES with more than 40 m^3 is necessary. The result of the calculation refers to an entire cooling operation in the free-cooling mode.

Statkraft Varme offers the possibility for feeding heat into the DH grid (Egil Evensen Helmer from Statkraft Varme 3/22/2015). To feed thermal energy into the grid, an exchange temperature of approximately 100°C must be reached. Additionally is feeding heat into the DH grid just possible during winter season, because of the high amount of excess heat in the summer season. Therefore, there is no need for buying extra heat during summer season (Egil Evensen Helmer from Statkraft Varme 3/22/2015).

The production cost from Statkraft Varme varies from zero in the summer (waste heat) to 50 øre/kWh (oil/gas) as peak load in the wintertime. As an indication it can be calculated with 15°-20 øre/kWh in the winter time (6 month) (Egil Evensen Helmer from Statkraft Varme 3/22/2015).

Hence, a temperature of approximately 100°C must be reached, the COP of a heat pump for a temperature difference of > 80°C between source and output temperature is smaller than 2 (Udo Leuschner). That means that half of the heat output energy is electrical input energy, which cost 70 øre/kWh (Egil Evensen Helmer from Statkraft Varme 3/22/2015) at the Risvollan area. Accordingly, the earning of every feeding in kWh must be higher than > 35 øre/kWh for being in the rentable frame. Not included in the price of 35 øre/kWh, are additional energy cost for pumps and other necessary devices, which will minimize the earning of the feeding in energy as well. The chance for a profitability way of feeding energy into the DH grid depends on the opportunity to do it during peak loads of the grid. Information about the peak load data from the DH grid are not available at that point.

It can be assumed that the proper use of the thermal energy production because of the higher reachable COP for heat pumps is more advantageous than feeding into the DH grid. Additionally can be summarized that the proper use of thermal energy that leads to a decrease of the energy consumption from the DH grid is more cost effective than feeding energy into the DH grid. Because of these statements, selling heat to the DH grid will not be considered further.

6 Levelized energy costs analysis

For making the energy concepts considerable from an economical point of view, the Levelized Energy Costs (LEC) are considered for each of the three energy concepts. The results of the calculations are given in NOK/kWh. Due to the current point of project progress not all information of costs are available. Therefore the frame conditions for the coming calculations must be identified. For cost estimations of the initial costs of construction and material experienced qualified persons from providing companies were consulted. Frame conditions for the following cost calculations are:

- Costs for the system construction are done as onetime self-financed investments at the beginning of the first year of construction
- Tax rate for the discount rate calculation is 0 % because of self-financing of the project costs.
- Lifetime of the energy systems is chosen to be 25 years, equal to the depreciation time of heating system (David Keeping, Sintef 2007)
- The costs for thermal energy distribution between the energy sources and the buildings are not included. They are assumed as equal for every concept
- Yearly maintenance costs are not included because of lacking detailed information at the current state of project. According to the received information of the consulted experts are BHE and ice TES nearly maintenance free
- Annual costs are including costs of external energy for operating the systems
- For determined prices in € it is used an actual exchange rate of 8.5 NOK/€
- Costs are given exclusive VAT

The calculated discount rate is equal for each LEC calculation of the different concepts. The increasing rate of the price of electrical power in Norway during the last year (03/2014 – 03/2015) is 2.2 %. The inflation rate of year 2014 is 2.07 % and the average of the nominal interest rate of 2014 is 2.1 % (www.ssb.no - Statistics Norway's Information Centre 2014). The discount rate r_E for 2014 is calculated as:

$$r_E = \frac{1}{(1+0.022)} \cdot \left[\frac{0.021 - 0.0207}{(1+0.0207)} - 0.022\right] = -0.021$$

The result of the discount rate calculation for the year 2014 is -2.1 % and is used for the following LEC calculations of the three energy concepts.

The energy efficiency factors provide information about the annual demand on electrical energy input to run the thermal energy systems. The additional demand of electrical energy is shown in Table 11. It is assumed that the cooling parts of the system are mainly operated in free cooling mode and the heat pumps are only switched on during peak load. Therefore, the SEER is estimated to 15 based on the reference EER from chapter 5. The SPF is transferred from the recommended values from chapter 5. The momentary electrical power prices to the customer in the project area of Risvollan is 0.7 NOK/kWh exclusive VAT (Egil Evensen Helmer from Statkraft Varme 3/22/2015).

Table 11: External energy input

	SPF	**SEER**	**Heat demand** [MWh/a]	**Cold demand** [MWh/a]	**External energy input** [MWh/a]
Energy concept 1	3.5	15	769	2.7	219.89
Energy concept 2	4.2	15	769	2.7	183.28
Energy concept 3	-	15	769	2.7	769.18

6.1 LEC of energy concept 1

The drilling costs for a geothermal well are mainly depending on the depth of the layer until the bedrock starts. As there is no exact information or test drillings available in the project area in Risvollan, the depth of the first layer before bedrock is assumed to be 51 m. This depth is equal to the test drillings south-east of the project area at the other street side of Blaklivegen as shown in the Report from the geotechnical department of Trondheim (Trondheim Kommune 2013). None of these test drillings reached bedrock. The reachable depth of each of the 48 boreholes is supposed to be 230 m because of the used equipment and available compressor pressure.

The costs for drilling through soil until reaching bedrock is approximately 1,000 NOK/m (Randi Kalskin Ramstad 2/17/2015). The cost estimation includes the installation of the BHE and the steel casing for stabilizing the soil (Randi Kalskin Ramstad 2/17/2015). The costs for drilling in bedrock are approximately are 250 NOK/m (Randi Kalskin Ramstad 2/17/2015). For removal and transportation of the excavated soil, have to be calculated additionally for each well 4,500 NOK (Hilde Anita Grandetrø from BÅSUM BORING TRØNDELAG AS 4/8/2015). The costs for a well and the entire grid are calculated as follow:

$$Costs_{well} = 51m \cdot 1{,}000\,{}^{NOK}/_{m} + 169m \cdot 250\,{}^{NOK}/_{m} + 4{,}500\,NOK = 97{,}750\,NOK$$

$$Costs_{BHE\ grid} = 97{,}750\,NOK \cdot 48 = 4{,}692{,}000\,NOK$$

Heat absorber tubes can be bought at the German technology market for 510 NOK/m² (60€/m²) excl. VAT (www.haustechnikdialog.de 2014). The used roof areal for the yield of 430 MWh/a is 1,776 m². The following costs are expected:

$$Costs_{heat\ absorber} = 510\,{}^{NOK}/_{m^2} \cdot 1{,}776m^2 = 905{,}760\,NOK$$

The initial costs of the thermal energy system are 5,597,760 NOK. The annual costs are 153,926 NOK/a.

$$Annual\ Costs = 219.894\ {}^{kWh}/_{a} \cdot 0.7\,{}^{NOK}/_{kWh} = 153{,}926\ {}^{NOK}/_{a}$$

With all available costs and the discount rate of - 2.1 %, the expected LEC of energy concept 1 assuming a lifetime of 25 year becomes:

$$LEC_{EC1} = \frac{\left(5{,}597{,}760\,NOK + \sum_{n=0}^{25}\frac{(153{,}926\,NOK)_n}{(1-0.021)^n}\right)}{\sum_{n=0}^{25}\frac{(271{,}700\,kWh)}{(1-0.021)^n}} = 1.167\ {}^{NOK}/_{kWh}$$

6.2 LEC of energy concept 2

The costs of the energy concept 2 consist of the construction and material for the 1,800 m³ ice TES and the heat absorbers, which cover a roof area of 4,185 m². The cost estimation for a 1,800 m³ ice TES is done by Matthias Rauch from the Viessmann company in Germany during the research work in march 2015. Matthias Rauch estimated the costs for the construction and material to 500,000 € (4,250,000 NOK). A more exactly calculation is possible at a later phase of the project, when more detailed information is available (Matthias Rauch from VIESSMANN 2/14/2015). The costs for the heat absorbers are 510 NOK/m².

$$Initial\ Costs = 4{,}250{,}000\ NOK + 4{,}185m^2 \cdot 510\ {}^{NOK}/_{m^2} = 6{,}384{,}350\ NOK$$

With a SPF of 4.2 and a SEER of 15 the additional yearly electrical energy demand of the system is 183,275 kWh/a.

$$Annual\ Costs = 183.275\ {}^{kWh}/_{a} \cdot 0.7\ {}^{NOK}/_{kWh} = 128{,}293\ {}^{NOK}/_{a}$$

With the discount rate of - 2.1 % in 2014, the Initial cost of 6,384,350 NOK and the Annual Costs of 183,275 kWh follows the calculation of the LEC of energy concept 2:

$$LEC_{EC2} = \frac{\left(6{,}284{,}350\ NOK + \sum_{n=0}^{25} \frac{(128{,}293\ NOK)_n}{(1-0.021)^n}\right)}{\sum_{n=0}^{25} \frac{(271{,}700\ kWh)}{(1-0.021)^n}} = 1.157\ {}^{NOK}/_{kWh}$$

The expected LEC is 1.16 NOK for every produced kWh during the life time of 25 years.

6.3 LEC of energy concept 3

The initial costs of energy concept 3 includes costs for the ice TES, heat absorber for leading the energy into the ice TES and the connecting fee of the project area to DH grid.

The smallest unit of an ice TES offered by Viessmann has a size of 50 m³. The calculated size in chapter 5.3 is 40.6 m³. A 50 m³ ice TES costs 55,000 € (467,500 NOK) (Matthias Rauch from VIESSMANN 2/14/2015). The needed absorber area for covering the cold load of the tank is estimated to 20 m².

The connecting costs to the DH grid is a onetime payment. The prices for connecting a single house is between 30,000 and 50,000 NOK. For a commercial or municipal building, the price of the fee is between 100.000 – 200.000 NOK (Amund Utne from Statkraft Varme 4/7/2015). In the Risvollan project case it is more usual to provide a bigger distribution central from where the buildings will be connected afterwards, instead of having an individual connection to each building. The fee for such a distribution central is estimated to 400,000 NOK. The initial cost are calculated as follow:

$$Initial\ Costs = 400{,}000\ NOK + 20m^2 \cdot 510\ {}^{NOK}/_{m^2} + 467{,}500NOK = 877{,}700\ NOK$$

The annual cost consists of heat from the DH grid and the used electrical energy for running the ice TES. The entire external energy demand is 769,180 kWh/a. The energy price to the customer from the district heating grid is often similar to the price for electric power and today it is in the Risvollan area about 70 øre/kWh exclusive VAT, (Egil Evensen Helmer from Statkraft Varme 3/22/2015). The annual costs are assumed in the following equation:

$$Annual\ Costs = 769.18\ {}^{kWh}/_{a} \cdot 0.7\ {}^{NOK}/_{kWh} = 538{,}426\ {}^{NOK}/_{a}$$

With the initial cost of 877,700 NOK, the annual costs of 538,426 NOK, a discount rate of -2.1 % and the lifetime of 25 year for a heating system are calculated the LEC of energy concept 3:

$$LEC_{EC3} = \frac{\left(877{,}700\ NOK + \sum_{n=0}^{25} \frac{(538{,}426\ NOK)_n}{(1-0.021)^n}\right)}{\sum_{n=0}^{25} \frac{(271{,}700\ kWh)}{(1-0.021)^n}} = 2.076\ {}^{NOK}/_{kWh}$$

The LEC of energy concept 3 is 2.08 NOK for every produced kWh during the life time of 25 years.

7 Discussions

7.1 Energy concepts and levelized energy costs

The energy profile of the buildings (Figure 21) shows that the expected cold demand (2.7 MWh/a) of the buildings compared with the heat demand (769 MWh/a) is very small. All three designed energy concepts shown in chapter 5 are able to deliver sufficient thermal energy to cover the necessary heat and cold demand of the buildings at the Risvollan project area during the year. The appropriate technologies for each energy concept are listed in Table 12.

Table 12: Appropriate technologies of the energy concepts

	Technologies
Energy concept 1	Geothermal well grid Solar heat absorber
Energy concept 2	Ice TES Solar heat absorber
Energy concept 3	District heating grid Ice TES Heat absorber

The priority during designing the energy concepts is focused on covering the heat demand, because of the much higher heat load of the buildings compared to the cold demand. All three energy concepts are exploiting the yearly heat reserves of the applied energy sources. Because of the high discrepancy of cold and heat energy, it can be expected, that in energy concept 1 & 2 there is a high amount of unused cold energy available. The unused surplus cold energy is available during recovering the geothermal wells and charging the ice TES in the summer season.

The initial costs as well as annual cost of each concept are varying as it can be seen in Table 13. The initial cost of concepts 1 & 2 are considerably higher than in energy concept 3. Through the high demand of external heat energy from the DH-grid the annual costs for energy concept 3 is notably higher compared to the both other concepts. The LEC after 25 years is almost equal for concepts 1 & 2 and at that time nearly half of the energy costs of concept 3.

Table 13: Summery of energy concepts costs

	Initial Costs [NOK]	Annual Costs [NOK]	$LEC_{25\ years}$ [NOK/kWh]
Energy concept 1	5,597,760	153,926	1.17
Energy concept 2	6,384,350	128,293	1.16
Energy concept 3	877,700	538,426	2.08

During the lifetime of 25 years the LEC of the three concepts evolve differently as it is presented in Figure 32. The costs for 1 kWh in the first 5 years are considerably higher for concept 1&2. The LEC of concept 3 is changing less during 25 years than the LEC of concept 1&2 do. After 10 years nearly the same price for all concepts will be reached. All three LEC are between 2.25 and 2.39 NOK for 1 kWh at this time. After 10 years of operation, the LEC of 1 produced kWh for the energy concept 1 & 2 is lower than the LEC of concept 3. The LEC of concept 3 is not changing significantly between 10 and 25 years of operation. Between these years a low decrease around 0.17 NOK/kWh is notable. A produced kWh of energy concept 1 & 2 over the lifetime of 25 years is significant lower than the kWh-costs of concept 3. The LEC of concept 1 & 2 are nearly harmonized throughout the lifetime of 25 years.

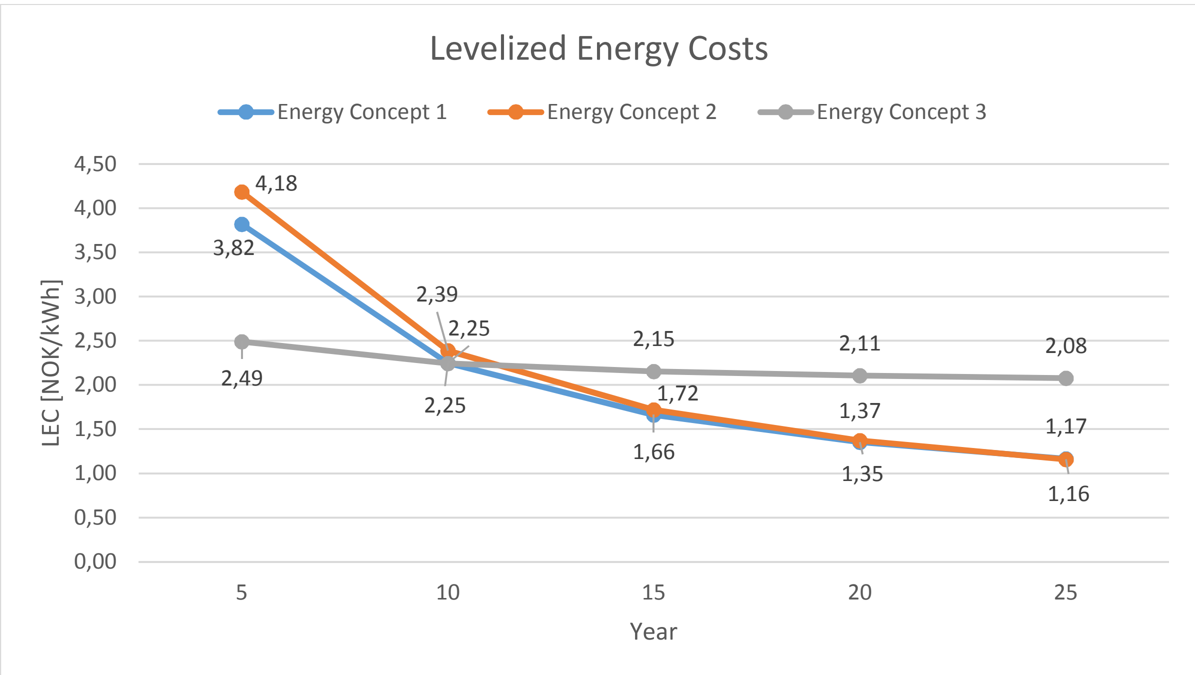

Figure 32: LEC during the lifetime of 25 years

Accordingly to the LEC results shown in Figure 32 it can be concluded that a concept with components of energy concept 1 & 2 are more cost efficient than concept 3 and that already after 12 years of operation. The higher investment costs of concept 1 & 2 pays off if a long-term operation is considered.

7.2 Data quality and uncertainty

The energy consumption of the planed buildings in the Risvollan project area in chapter 4 are calculated with SIMIEN and under the frame conditions to reach the standards of NS 3031 and NS 3701. The models of the buildings for the Simien calculations have been designed with all available information and accessible data, how documented in chapter 3.2. It can be assumed that new construction plans will be more detailed and differ from the first ideas of the project study plans used during this Thesis.

The ratios of the energy efficiency of the thermal energy systems as well as the components are mainly derived from literature recommendations and suitable reference projects. Hence, the energy efficiency ratios are very individual values for every energy system and depending on a plurality of factors and chosen components, it has to be assumed that the ratios can be differ from the declared values.

A LEC method includes in the best-case detailed costs information about financing, the construction and the operation costs. At the current status of project not all detailed input costs information are available, providing of the necessary information is in some cases too complex and limitations had to be made for the calculations in chapter 6. The quality of the results from the LEC calculations are depending on the quality of the estimations from the consulted experts. All available and in this Thesis documented details of the current project status have been mentioned to the consulted experts.

8 Conclusions and further work

The results of this Master's Thesis have shown that the concepts of thermal energy production and storage at the Risvollan area are representing a cost and energy efficient solution. Furthermore, they are a serious alternative to the thermal energy supply from external grids. The ambitions of Energy21 are fulfilled through the utilization of energy sources from renewable energies and thermal energy storage systems. It can be assumed that the implementation of such systems are in accordance with the national energy strategies Energi21.

Depending on the availability of more detailed information about the Risvollan project, the energy concepts can be specified further. More detail information are:

- Thermal and hydrological data from the underground of test drillings and a thermal respond test
- Detailed information and construction plans from the buildings and the Risvollan project area

Based on the more detailed information and plans, the energy concepts can be more specified. Suggestion for further work are:

- A specified energy analyses of the buildings
- A simulation of a detailed thermal performance of the underground for operation of the geothermal well grid
- Technical simulation and optimization of a heat source and storage management system for the chosen concept
- More detailed calculation of the Life Cycle Costs for the concepts
- Consideration of subsidies opportunities for the concepts
- A schedule for financing models
- Designing a smart distribution grid for improving the SPF, SEER and COP's
- Concepts for a higher exploitation of the cold energy during recovering the underground from geothermal well grid and the ice TES of concept 2
- Checking legal and political frame conditions for implementation

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Appendix A: SIMIEN Results of annual simulations

SIMIEN

Resultater årssimulering

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Prosjekt: Barnehagge
Sone: BH

Energibudsjett		
Energipost	Energibehov	Spesifikt energibehov
1a Romoppvarming	27919 kWh	39,9 kWh/m²
1b Ventilasjonsvarme (varmebatterier)	13227 kWh	18,9 kWh/m²
2 Varmtvann (tappevann)	14045 kWh	20,1 kWh/m²
3a Vifter	4988 kWh	7,1 kWh/m²
3b Pumper	1173 kWh	1,7 kWh/m²
4 Belysning	9240 kWh	13,2 kWh/m²
5 Teknisk utstyr	3080 kWh	4,4 kWh/m²
6a Romkjøling	0 kWh	0,0 kWh/m²
6b Ventilasjonskjøling (kjølebatterier)	137 kWh	0,2 kWh/m²
Totalt netto energibehov, sum 1-6	73809 kWh	105,4 kWh/m²

Levert energi til bygningen (beregnet)		
Energivare	Levert energi	Spesifikk levert energi
1a Direkte el.	18480 kWh	26,4 kWh/m²
1b El. Varmepumpe	24918 kWh	35,6 kWh/m²
1c El. solenergi	0 kWh	0,0 kWh/m²
2 Olje	0 kWh	0,0 kWh/m²
3 Gass	0 kWh	0,0 kWh/m²
4 Fjernvarme	0 kWh	0,0 kWh/m²
5 Biobrensel	0 kWh	0,0 kWh/m²
Annen energikilde	0 kWh	0,0 kWh/m²
Totalt levert energi, sum 1-6	43398 kWh	62,0 kWh/m²

SIMIEN

Resultater årssimulering

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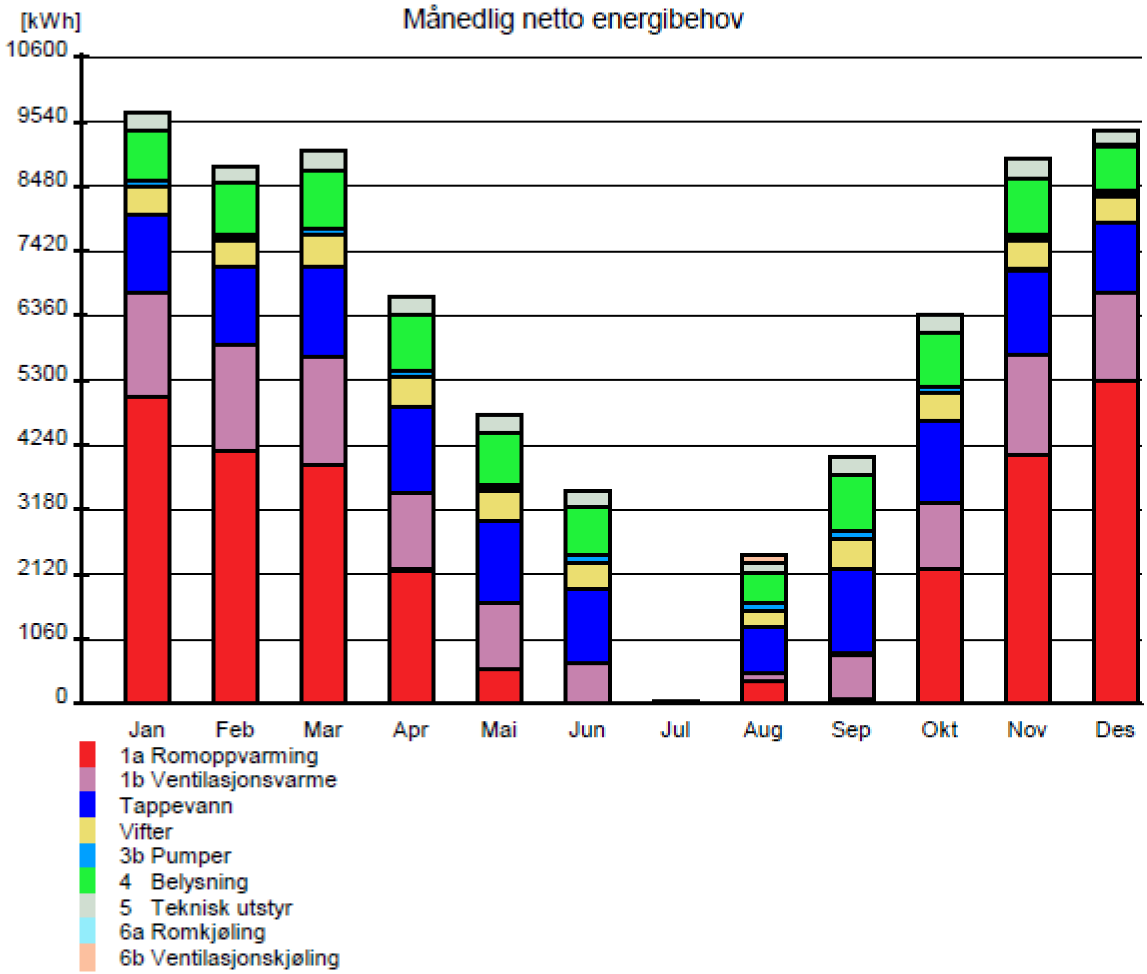

SIMIEN

Resultater årssimulering

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Sone: Boliger mot nord

Energibudsjett		
Energipost	Energibehov	Spesifikt energibehov
1a Romoppvarming	27445 kWh	50,8 kWh/m²
1b Ventilasjonsvarme (varmebatterier)	4275 kWh	7,9 kWh/m²
2 Varmtvann (tappevann)	24114 kWh	44,7 kWh/m²
3a Vifter	4565 kWh	8,5 kWh/m²
3b Pumper	500 kWh	0,9 kWh/m²
4 Belysning	6532 kWh	12,1 kWh/m²
5 Teknisk utstyr	9461 kWh	17,5 kWh/m²
6a Romkjøling	0 kWh	0,0 kWh/m²
6b Ventilasjonskjøling (kjølebatterier)	54 kWh	0,1 kWh/m²
Totalt netto energibehov, sum 1-6	76944 kWh	142,5 kWh/m²

Levert energi til bygningen (beregnet)		
Energivare	Levert energi	Spesifikk levert energi
1a Direkte el.	21057 kWh	39,0 kWh/m²
1b El. Varmepumpe	25400 kWh	47,0 kWh/m²
1c El. solenergi	0 kWh	0,0 kWh/m²
2 Olje	0 kWh	0,0 kWh/m²
3 Gass	0 kWh	0,0 kWh/m²
4 Fjernvarme	0 kWh	0,0 kWh/m²
5 Biobrensel	0 kWh	0,0 kWh/m²
Annen energikilde	0 kWh	0,0 kWh/m²
Totalt levert energi, sum 1-6	46458 kWh	86,0 kWh/m²

SIMIEN

Resultater årssimulering

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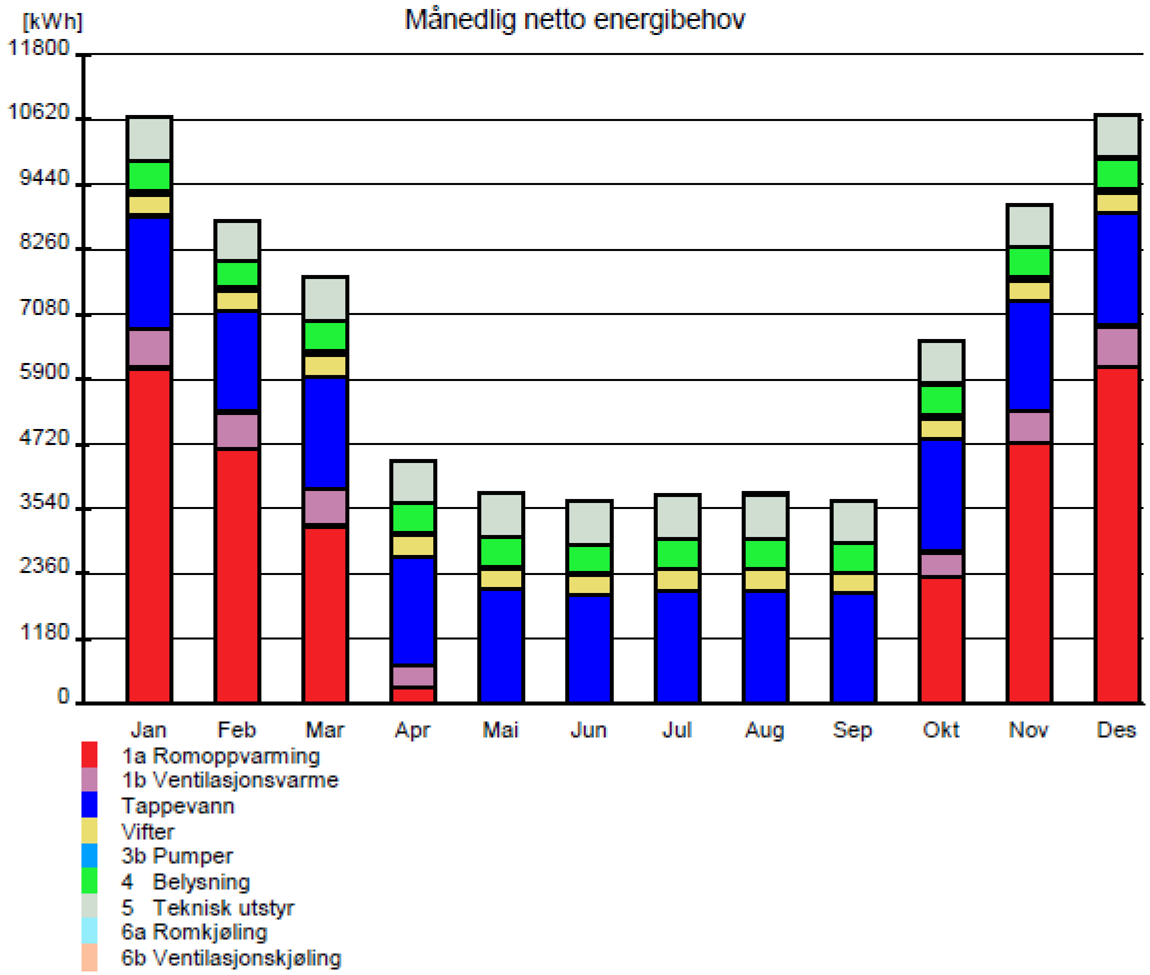

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Energibudsjett		
Energipost	Energibehov	Spesifikt energibehov
1a Romoppvarming	52 kWh	0,0 kWh/m²
1b Ventilasjonsvarme (varmebatterier)	623 kWh	0,3 kWh/m²
2 Varmtvann (tappevann)	48037 kWh	20,3 kWh/m²
3a Vifter	50758 kWh	21,4 kWh/m²
3b Pumper	1843 kWh	0,8 kWh/m²
4 Belysning	259414 kWh	109,6 kWh/m²
5 Teknisk utstyr	570860 kWh	241,1 kWh/m²
6a Romkjøling	0 kWh	0,0 kWh/m²
6b Ventilasjonskjøling (kjølebatterier)	12557 kWh	5,3 kWh/m²
Totalt netto energibehov, sum 1-6	944146 kWh	398,7 kWh/m²

Levert energi til bygningen (beregnet)		
Energivare	Levert energi	Spesifikk levert energi
1a Direkte el.	882876 kWh	372,8 kWh/m²
1b El. Varmepumpe	27165 kWh	11,5 kWh/m²
1c El. solenergi	0 kWh	0,0 kWh/m²
2 Olje	0 kWh	0,0 kWh/m²
3 Gass	0 kWh	0,0 kWh/m²
4 Fjernvarme	0 kWh	0,0 kWh/m²
5 Biobrensel	0 kWh	0,0 kWh/m²
Annen energikilde	0 kWh	0,0 kWh/m²
Totalt levert energi, sum 1-6	910041 kWh	384,3 kWh/m²

SIMIEN

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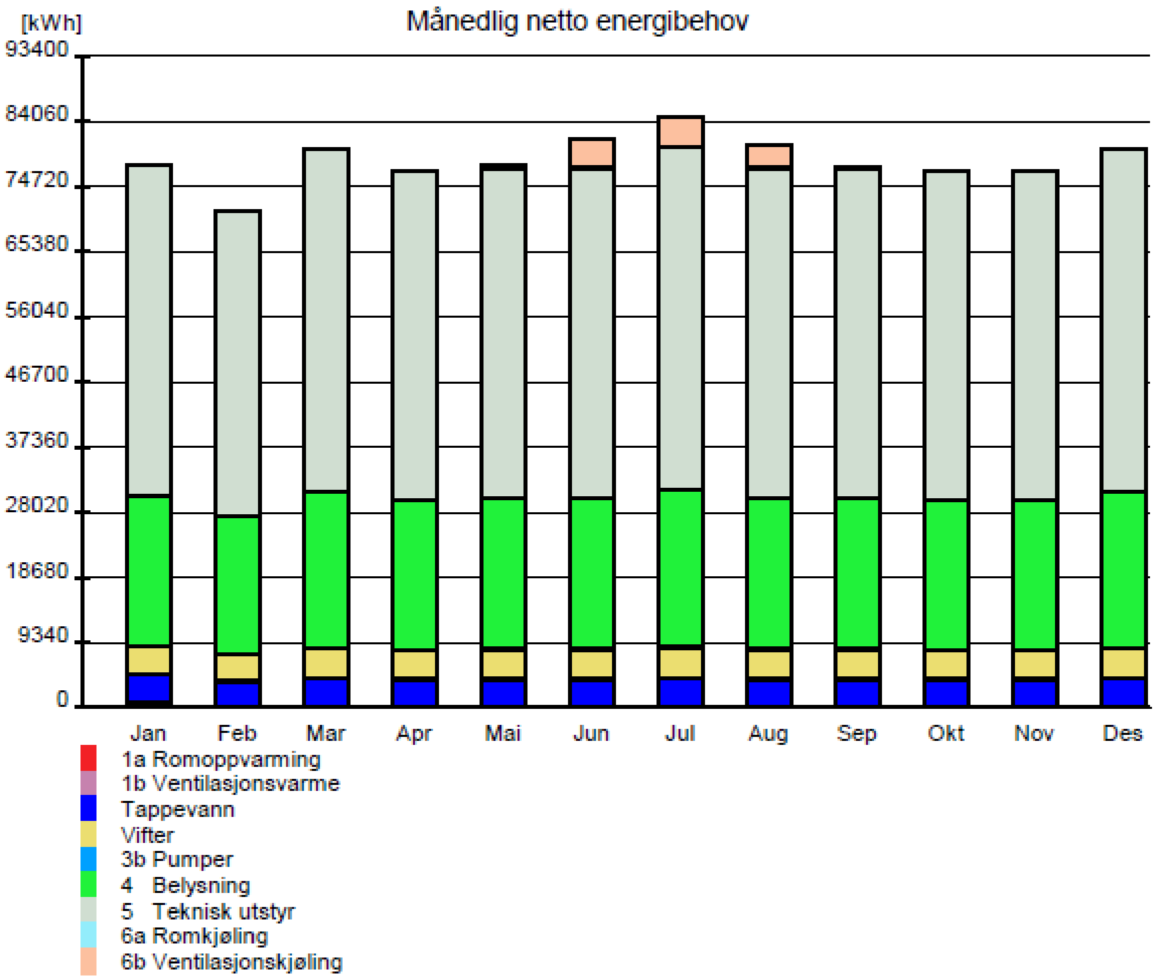

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Energipost	Energibehov	Spesifikt energibehov
1a Romoppvarming	339 kWh	0,1 kWh/m²
1b Ventilasjonsvarme (varmebatterier)	104936 kWh	44,3 kWh/m²
2 Varmtvann (tappevann)	75653 kWh	31,9 kWh/m²
3a Vifter	30272 kWh	12,8 kWh/m²
3b Pumper	1471 kWh	0,6 kWh/m²
4 Belysning	46972 kWh	19,8 kWh/m²
5 Teknisk utstyr	49444 kWh	20,9 kWh/m²
6a Romkjøling	0 kWh	0,0 kWh/m²
6b Ventilasjonskjøling (kjølebatterier)	956 kWh	0,4 kWh/m²
Totalt netto energibehov, sum 1-6	310043 kWh	130,9 kWh/m²

Levert energi til bygningen (beregnet)		
Energivare	Levert energi	Spesifikk levert energi
1a Direkte el.	128158 kWh	54,1 kWh/m²
1b El. Varmepumpe	82622 kWh	34,9 kWh/m²
1c El. solenergi	0 kWh	0,0 kWh/m²
2 Olje	0 kWh	0,0 kWh/m²
3 Gass	0 kWh	0,0 kWh/m²
4 Fjernvarme	0 kWh	0,0 kWh/m²
5 Biobrensel	0 kWh	0,0 kWh/m²
Annen energikilde	0 kWh	0,0 kWh/m²
Totalt levert energi, sum 1-6	210781 kWh	89,0 kWh/m²

SIMIEN

Resultater årssimulering

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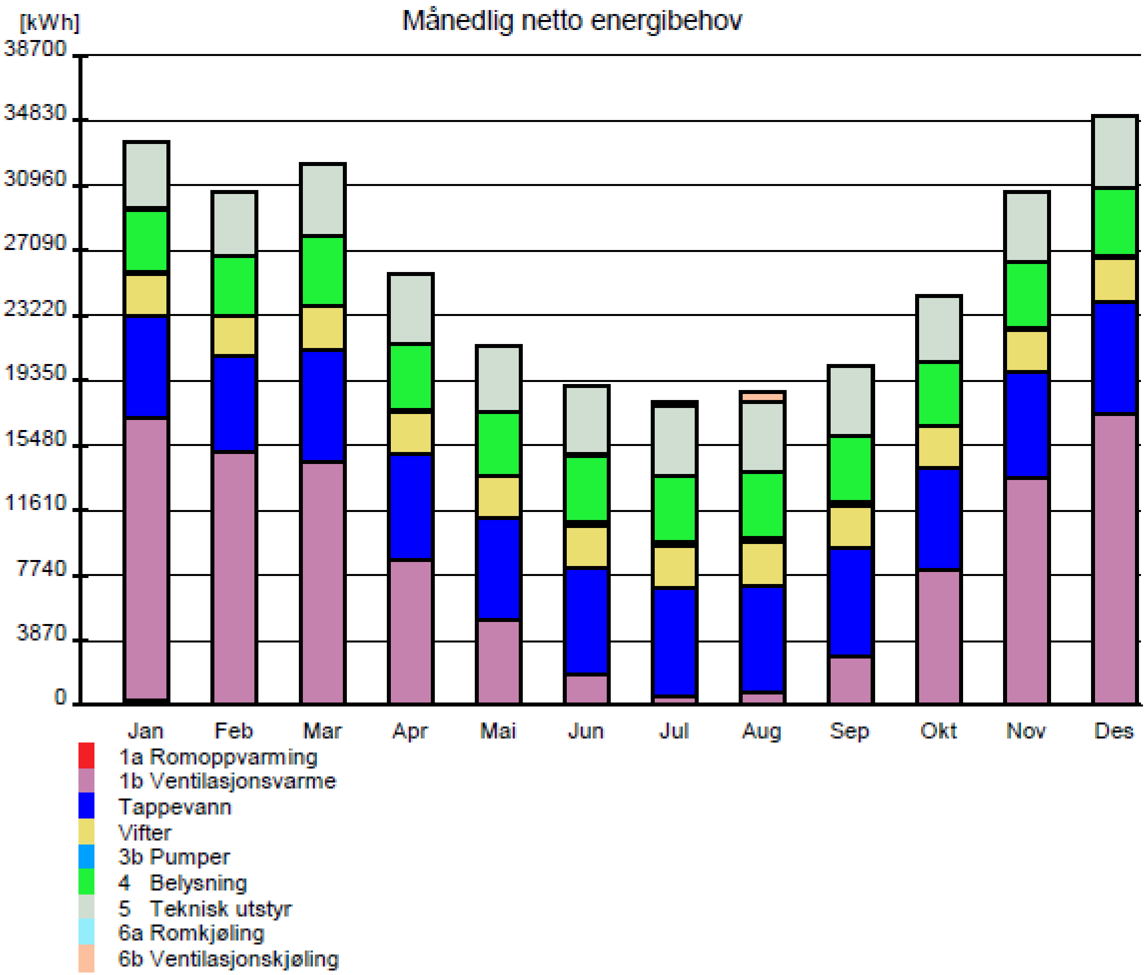

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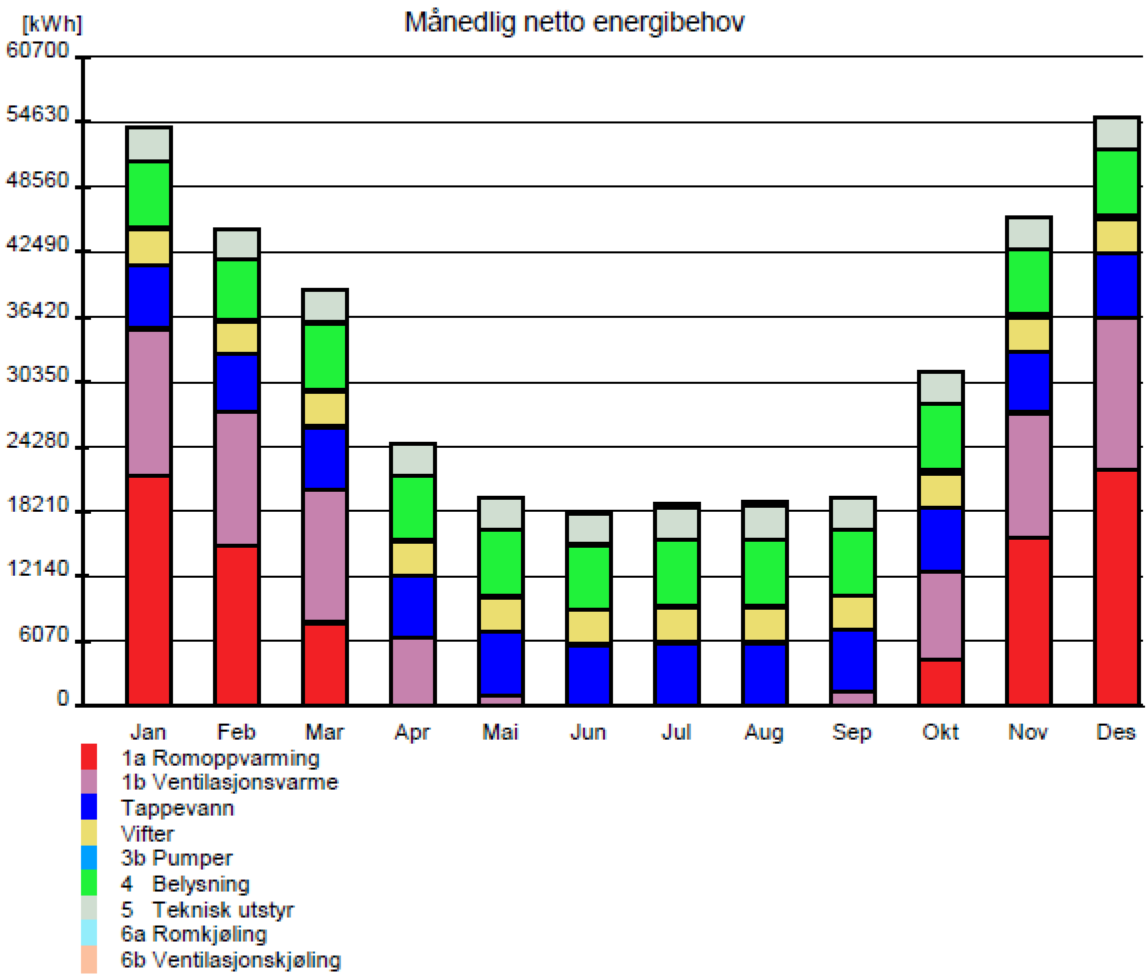
Energibudsjett		
Energipost	Energibehov	Spesifikt energibehov
1a Romoppvarming	86717 kWh	55,2 kWh/m²
1b Ventilasjonsvarme (varmebatterier)	81445 kWh	51,9 kWh/m²
2 Varmtvann (tappevann)	70113 kWh	44,7 kWh/m²
3a Vifter	39208 kWh	25,0 kWh/m²
3b Pumper	2062 kWh	1,3 kWh/m²
4 Belysning	73342 kWh	46,7 kWh/m²
5 Teknisk utstyr	36671 kWh	23,4 kWh/m²
6a Romkjøling	0 kWh	0,0 kWh/m²
6b Ventilasjonskjøling (kjølebatterier)	714 kWh	0,5 kWh/m²
Totalt netto energibehov, sum 1-6	390273 kWh	248,6 kWh/m²

Levert energi til bygningen (beregnet)		
Energivare	Levert energi	Spesifikk levert energi
1a Direkte el.	151284 kWh	96,4 kWh/m²
1b El. Varmepumpe	107628 kWh	68,6 kWh/m²
1c El. solenergi	0 kWh	0,0 kWh/m²
2 Olje	0 kWh	0,0 kWh/m²
3 Gass	0 kWh	0,0 kWh/m²
4 Fjernvarme	0 kWh	0,0 kWh/m²
5 Biobrensel	0 kWh	0,0 kWh/m²
Annen energikilde	0 kWh	0,0 kWh/m²
Totalt levert energi, sum 1-6	258912 kWh	164,9 kWh/m²

SIMIEN

Resultater årssimulering

Simuleringsnavn: Omsorgsboliger - Årssimulering
Tid/dato simulering: 16:06 3/12-2014
Programversjon: 5.022
Simuleringsansvarlig:
Firma: Undervisningslisens
Inndatafil: C:\Users\SHU\Desktop\Sintef\Risvollan\SIMIEN\Omsorgsboliger.smi
Prosjekt: Omsorgsboliger
Sone: Omsorgsboliger



SIMIEN

Resultater årssimulering

Simuleringsnavn: Ssykehjem - Årssimulering
Tid/dato simulering: 16:08 3/12-2014
Programversjon: 5.022
Simuleringsansvarlig:
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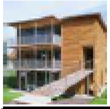
Prosjekt: Sykehjem
Sone: Alle soner

Energibudsjett		
Energipost	Energibehov	Spesifikt energibehov
1a Romoppvarming	14760 kWh	7,8 kWh/m²
1b Ventilasjonsvarme (varmebatterier)	92885 kWh	49,1 kWh/m²
2 Varmtvann (tappevann)	84461 kWh	44,7 kWh/m²
3a Vifter	47203 kWh	25,0 kWh/m²
3b Pumper	2041 kWh	1,1 kWh/m²
4 Belysning	88323 kWh	46,7 kWh/m²
5 Teknisk utstyr	44161 kWh	23,4 kWh/m²
6a Romkjøling	0 kWh	0,0 kWh/m²
6b Ventilasjonskjøling (kjølebatterier)	860 kWh	0,5 kWh/m²
Totalt netto energibehov, sum 1-6	374693 kWh	198,3 kWh/m²

Levert energi til bygningen (beregnet)		
Energivare	Levert energi	Spesifikk levert energi
1a Direkte el.	181728 kWh	96,2 kWh/m²
1b El. Varmepumpe	86892 kWh	46,0 kWh/m²
1c El. solenergi	0 kWh	0,0 kWh/m²
2 Olje	0 kWh	0,0 kWh/m²
3 Gass	0 kWh	0,0 kWh/m²
4 Fjernvarme	0 kWh	0,0 kWh/m²
5 Biobrensel	0 kWh	0,0 kWh/m²
Annen energikilde	0 kWh	0,0 kWh/m²
Totalt levert energi, sum 1-6	268620 kWh	142,1 kWh/m²



SIMIEN

Resultater årssimulering

Simuleringsnavn: Ssykehjem - Årssimulering
Tid/dato simulering: 16:08 3/12-2014
Programversjon: 5.022
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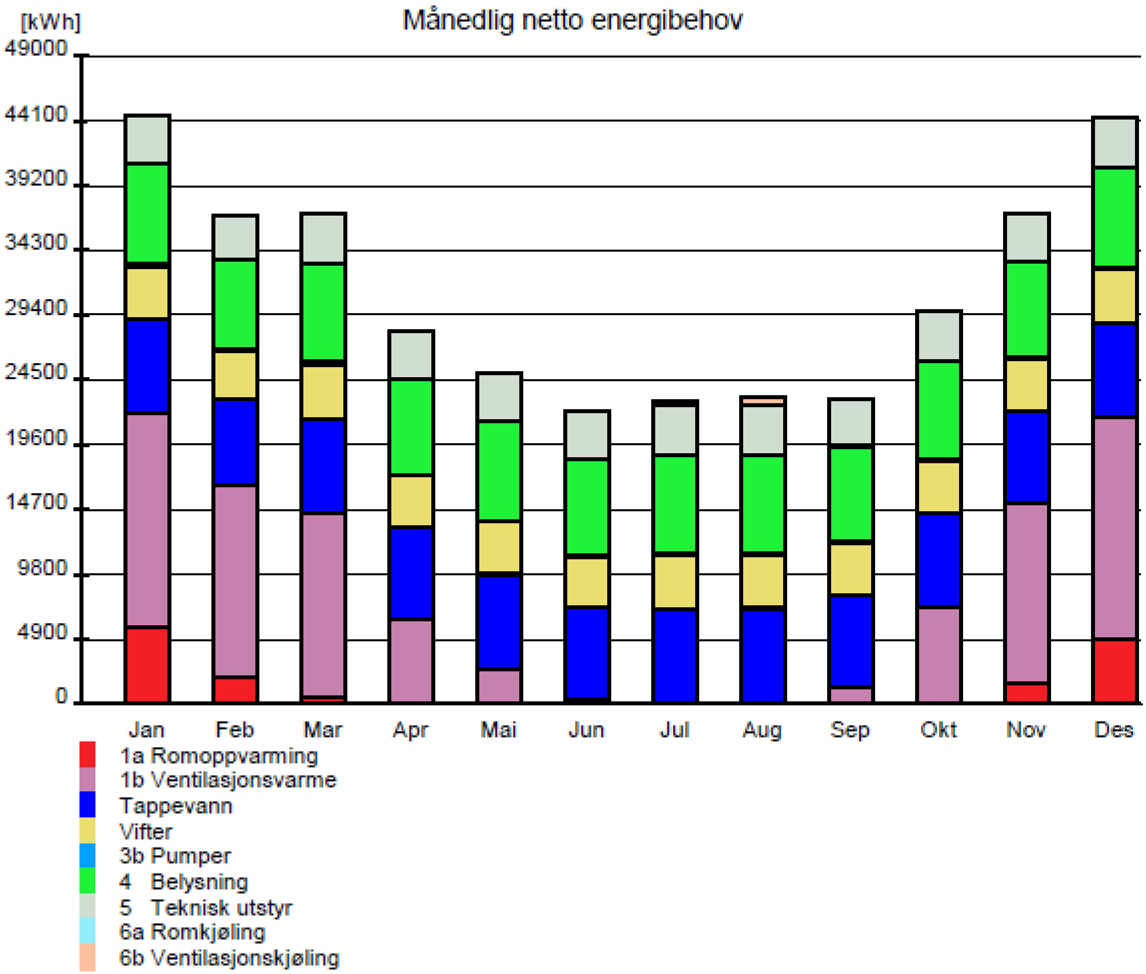
Prosjekt: Sykehjem
Sone: Alle soner



Appendix B: EED Design Data of Energy Concept 1

EED Version 3,16 - www,buildingphysics,com - license for WWW,NTNU,NO

Input file:C:\Users\SHU\Desktop\Sintef\Risvollan\EED\Risvollan\Risvollan,dat

This output file:RISVOLLAN,OUT Date: 03,05,2015 Time: 20:24:49

MEMORY NOTES FOR PROJECT

QUICK FACTS

Cost	-
Number of boreholes	48
Borehole depth	230,00 m
Total borehole length	11040,00 m

D E S I G N D A T A

GROUND:

Ground thermal conductivity	1,330 W/(m·K)
Ground heat capacity	2,300 MJ/(m³·K)
Ground surface temperature	4,70 °C
Geothermal heat flux	0,0500 W/m²

BOREHOLE:

Configuration:	425 ("48 : 6 x 8 rectangle")
Borehole depth	230,00 m
Borehole spacing	7,00 m
Borehole installation	Single-U
Borehole diameter	140,00 mm
U-pipe diameter	32,000 mm
U-pipe thickness	3,000 mm
U-pipe thermal conductivity	0,420 W/(m·K)
U-pipe shank spacing	81,000 mm
Filling thermal conductivity	0,600 W/(m·K)
Contact resistance pipe/filling	0,0000 (m·K)/W

THERMAL RESISTANCES

Borehole therm, res, fluid/ground	0,1000 (m·K)/W
Borehole therm, res, internal	0,5000 (m·K)/W

Internal heat transfer between upward and downward channel(s) is considered,

HEAT CARRIER FLUID

Thermal conductivity	0,4800 W/(m·K)
Specific heat capacity	3795,000 J/(Kg·K)
Density	1052,000 Kg/m³
Viscosity	0,005200 Kg/(m·s)
Freezing point	-14,0 °C
Flow rate per borehole	3,800 l/s

BASE LOAD

Annual DHW load	0,00 MWh
Annual heating load (DHW excluded)	769,00 MWh
Annual cooling load	430,00 MWh
Seasonal performance factor (DHW)	3,00
Seasonal performance factor (heating)	3,50
Seasonal performance factor (cooling)	3,50

<u>Monthly energy profile [MWh]</u>

Month	Factor	Heat load	Factor	Cool load	Ground load
JAN	0,150	115,35	0,000	0,00	82,393
FEB	0,130	99,97	0,000	0,00	71,407
MAR	0,110	84,59	0,000	0,00	60,421
APR	0,070	53,83	0,130	55,90	-33,421
MAY	0,050	38,45	0,191	82,13	-78,131
JUN	0,040	30,76	0,200	86,00	-88,600
JUL	0,030	23,07	0,220	94,60	-105,150
AUG	0,040	30,76	0,161	69,23	-67,039
SEP	0,040	30,76	0,066	28,38	-14,517
OCT	0,080	61,52	0,032	13,76	26,251
NOV	0,110	84,59	0,000	0,00	60,421
DEC	0,150	115,35	0,000	0,00	82,393
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Total	1,000	769,00	1,000	430,00	-3,571

PEAK LOAD

Monthly peak powers [kW]

Month	Peak heat	Duration	Peak cool	Duration [h]
JAN	212,00	10,0	90,00	0,0
FEB	212,00	12,0	90,00	8,0
MAR	212,00	6,0	90,00	25,0
APR	212,00	2,0	90,00	25,0
MAY	212,00	0,0	90,00	32,0
JUN	212,00	0,0	90,00	34,0
JUL	212,00	0,0	90,00	40,0
AUG	212,00	0,0	90,00	25,0
SEP	212,00	0,0	90,00	32,0
OCT	212,00	4,0	90,00	8,0
NOV	212,00	12,0	90,00	0,0
DEC	212,00	10,0	90,00	0,0

Number of simulation years 25

First month of operation JAN

C A L C U L A T E D V A L U E S

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Total borehole length 11040,00 m

THERMAL RESISTANCES

Effective borehole thermal res, 0,1002 (m·K)/W

SPECIFIC HEAT EXTRACTION RATE [W/m]

Month	Base load	Peak heat	Peak cool
JAN	10,22	13,72	-10,48
FEB	8,86	13,72	-10,48
MAR	7,50	13,72	-10,48
APR	-4,15	13,72	-10,48
MAY	-9,69	13,72	-10,48
JUN	-10,99	13,72	-10,48
JUL	-13,05	13,72	-10,48
AUG	-8,32	13,72	-10,48

SEP	-1,80	13,72	-10,48
OCT	3,26	13,72	-10,48
NOV	7,50	13,72	-10,48
DEC	10,22	3,72	-10,48

BASE LOAD: MEAN FLUID TEMPERATURES (at end of month) [°C]

Year	1	2	5	10	25
JAN	3,97	3,66	3,44	3,48	3,58
FEB	4,20	4,03	3,96	3,97	4,05
MAR	4,64	4,54	4,62	4,59	4,65
APR	10,21	10,22	10,42	10,36	10,39
MAY	13,30	13,38	13,65	13,58	13,59
JUN	14,38	14,50	14,76	14,71	14,71
JUL	15,74	15,92	16,10	16,10	16,09
AUG	13,77	13,94	14,01	14,06	14,06
SEP	10,66	10,77	10,70	10,79	10,82
OCT	8,12	8,07	7,93	8,04	8,10
NOV	5,80	5,61	5,50	5,61	5,68
DEC	4,06	3,81	3,76	3,84	3,93

BASE LOAD: YEAR 25
Minimum mean fluid temperature 3,58 °C at end of JAN
Maximum mean fluid temperature 16,09 °C at end of JUL

PEAK HEAT LOAD: MEAN FLUID TEMPERATURES (at end of month) [°C]

Year	1	2	5	10	25
JAN	3,15	2,84	2,62	2,66	2,76
FEB	3,01	2,84	2,77	2,77	2,85
MAR	3,37	3,27	3,35	3,32	3,38
APR	7,73	7,74	7,94	7,88	7,92
MAY	13,30	13,38	13,65	13,58	13,59
JUN	14,38	14,50	14,76	14,71	14,71
JUL	15,74	15,92	16,10	16,10	16,09
AUG	13,77	13,94	14,01	14,06	14,06
SEP	10,66	10,77	10,70	10,79	10,82
OCT	6,23	6,19	6,05	6,16	6,21
NOV	4,27	4,08	3,97	4,08	4,15
DEC	3,24	2,99	2,94	3,02	3,11

PEAK HEAT LOAD: YEAR 25

Minimum mean fluid temperature 2,76 °C at end of JAN

Maximum mean fluid temperature 16,09 °C at end of JUL

PEAK COOL LOAD: MEAN FLUID TEMPERATURES (at end of month) [°C]

Year	1	2	5	10	25
JAN	3,97	3,66	3,44	3,48	3,58
FEB	8,49	8,32	8,25	8,26	8,34
MAR	9,85	9,76	9,84	9,80	9,86
APR	12,04	12,06	12,26	12,20	12,23
MAY	13,54	13,62	13,89	13,82	13,83
JUN	14,22	14,34	14,60	14,56	14,55
JUL	14,92	15,10	15,28	15,28	15,27
AUG	14,40	14,57	14,64	14,68	14,69
SEP	13,31	13,42	13,35	13,44	13,46
OCT	11,17	11,12	10,98	11,09	11,14
NOV	5,80	5,61	5,50	5,61	5,68
DEC	4,06	3,81	3,76	3,84	3,93

PEAK COOL LOAD: YEAR 25

Minimum mean fluid temperature 3,58 °C at end of JAN

Maximum mean fluid temperature 15,27 °C at end of JUL