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Geothermal Energy at Oslo Airport Gardermoen

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Master of Science in Product Design and Manufacturing
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MASTER THESIS

for

student Karine Huuse and student Vilde Moxnes

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Geothermal energy at Gardermoen airport

Geotermisk energy ved Gardermoen flyplass

Background and objective

Deep Geothermal energy refers to heat extracted from boreholes several kilometers deep in the bedrock. Traditionally this has been done in areas where there are naturally occurring hot springs.

Geothermal energy can be utilized through an Engineered Geothermal System (EGS). This is a technology which is still in its research state. Naturally, the areas with highest potential have attracted most attention and the ongoing EGS projects are mostly aiming at electricity production. However, through direct use in a district heating network it is possible to exploit also low temperature resources with a high thermal efficiency. The Norwegian company, Rock Energy AS has developed a method to extract geothermal energy through engineering a subsurface heat exchanger with drilled pathways. This is a novel concept in the exploitation of geothermal energy.

The extraction or mining of heat through an EGS can provide clean energy for electricity and heat production with limited emissions or footprint. There are, however, emissions related to both the construction phase and the continuous operation of such systems. To quantify the environmental impact, a life-cycle-assessment (LCA) can be performed.

This project will be a continuation of a previous student-project work where a gas fired district heating installation in Lier, Norway, was analyzed, with the aim to provide basis for dimensioning of a geothermal installation. Within the project work, also the fundamental parts within a LCA for an EGS installation were established.

This thesis has two main objectives, the first constituting a technical analysis of the energy system at Gardermoen Airport, Norway and the integration of an EGS as base load provider. The second objective is to perform an LCA analysis, based on the EGS concept developed by Rock Energy AS. This analysis will provide valuable information on the environmental impact for such systems.

The following tasks are to be considered:

Part 1:

1. Collect and present the relevant information regarding the energy system at Gardermoen Airport.
2. Perform an analysis of the existing energy system.
3. Dimension a geothermal installation.
4. Integrate the proposed geothermal installation with the present energy system.
5. Suggest further work.

Part 2:

1. Gather information required to perform the LCA analysis.
2. Perform the LCA.
3. Quantify uncertainties within the analysis.
4. Make suggestion for further work.

All tasks are to be performed as a collaborative effort by both candidates.

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.

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

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

Department of Energy and Process Engineering, 16. January 2012

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Preface

This master's thesis is carried out at the Norwegian University of Science and Technology, NTNU in Trondheim, and is the result of collaboration between Karine Huuse and Vilde Moxnes throughout spring semester 2012.

The project comprises 30 credits in the 10^{th} and last semester of our master degree at the Department of Energy and Process Engineering.

During our work, a number of people have contributed with support, encouragement and constructive feedback. First we would like to thank our supervisor Erling Næss and co-supervisor Otto Sønju for their guidance throughout this process. A special thanks to co-supervisors Henrik Holmberg and Thomas Gibon, who have always been available with advice and support. We would also like to thank Øyvind Nilsen and Fred-Arne Halvorsen at Hafslund for access to operational data.

Trondheim, June 2012

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Abstract

Rock Energy is a Norwegian company with a patented solution for drilling deep geothermal wells, for exploitation of deep geothermal energy from Hot Dry Rocks. The concept involves a drilled sub-surface heat exchanger, referred to as cross wells. The concept is well suited for production of heat for direct heat applications. In this thesis an analysis of the existing district heating plant at Oslo Airport Gardermoen has been conducted, together with examining possibilities of implementing geothermal energy as base load at the plant. A geothermal design that could meet the needs of the district heating plant has been established, and for evaluating the geothermal system in an environmental perspective an analysis based on LCA methodology has been conducted.

Hafslund operates two district heating centrals at Gardermoen (Gardermoen heating central and a smaller mobile central) for which both have been analyzed to determine the potential for implementing deep geothermal energy as base load for the systems. Gardermoen heating central is connected to the airport and to the area close to the airport. This central is again connected to the mobile heating central, which is situated near the industrial estate south-east of the airport. Based on Hafslund's production data from February 2011 to January 2012, a heat load duration curve for the two existing centrals have been established. When adding the two curves together the duration curve show a maximum load of 25,7 MW at present, and a yearly energy production of 74 GWh. The mobile central accounts for only 7,2% of the total load and heat production at present.

Future heat demand in the Gardermoen area is expected to increase beyond existing capacity. Hafslund is therefore considering to increase the capacity of both their district heating centrals. The enlargement plans involves that the heating central will be expanded to a design load of 37,4 MW (24 MW at present), while the mobile central need to be increased to a design load of 15,2 MW (1,7 MW at present). Assessment of the geothermal installation showed that it is preferable to include the geothermal system in the base load of the mobile central. The additional geothermal capacity will cover 10 MW, and thus deliver 65% of the required heat load and 90% of the energy production from the mobile central.

The geothermal installation was designed using the spreadsheet "Geocalc". The outputs from Geocalc are used in an analysis of the environmental performance of the designed system through a Life Cycle Assessment (LCA). LCA introduces a technique to assess environmental impacts associated with all stages of a product's life from "cradle to grave".

The report aims at giving normative results for the environmental impacts of a geothermal installation at Gardermoen. The method provides the ability to quantitatively compare results to other sources of heat provision processes for district heating. It is important to emphasize that the analysis has provided an overview of the potential environmental impact, and not necessarily the actual results of environmental consequences. The system analyzed has a thermal output of 10 MW, lifetime of 30 years, 5000 annual operating hours.

The functional unit of district heating produced is kWh. The analysis is based on the main contributing processes to construction, operation and demolition of Rock Energy's geothermal system. The district heating grid is not included in the analysis, as it is already in place at the site. Each contributing process has been systematically validated. It is however uncertainties associated with the data collection mainly due to contradictory information gathered. The information considered to be mostly uncertain is the energy consumption used for drilling purposes.

Possible scenarios for the energy supply to drilling were established. These scenarios were simulated in a system model in Excel. The model is based on data and information gathered from existing literature, the database Ecoinvent, published reports and personal communication with drilling experts and specialists within the relevant fields of study. The results are assessed for the following impact categories: Climate change, metal depletion, fossil depletion, terrestrial acidification and freshwater eutrophication. The evaluated potential energy sources for the drilling operation are electricity from the Norwegian grid, electricity from the European grid, and diesel.

The climate change category has especially been in focus when conducting the simulations and this category shows large spread in the results, from 0,9993 g CO_2-eq/kWh for the best scenario to 23,6 g CO_2-eq/kWh for the worst scenario. As expected, the analysis concludes that electricity from the Norwegian grid for the drilling is preferable. For a geothermal system in Europe, the results show that it would be advantageous to use diesel as energy supply for the drilling operation instead of European electricity mix, for which the emissions are doubled.

For the metal depletion impact category, the variation of energy supply to drilling cause the least fluctuation. This is also the only impact category where the Norwegian electricity mix has higher impacts than for the diesel consumption. This can be explained by the infrastructure related to electricity transmission.

The results of the study have been compared to other heat sources for district heating (waste incineration, biofuel and solar thermal). The comparison shows that from an LCA perspective geothermal energy based on Rock Energy's concept is an environmentally friendly energy supplier for district heating. The studies compared are however based on varying assumptions, and thus a generalized conclusion cannot be drawn from this.

Sammendrag

Rock Energy AS er et norsk selskap med en patentert løsning for boring av dype geotermiske brønner for utnyttelse av energi fra «Hot Dry Rocks» (HDR). Konseptet innebærer en undergrunns varmeveksler som bores mellom en injeksjons- og produksjonsbrønn. Konseptet er godt egnet for produksjon av varme til direkte bruk (for eksempel fjernvarme). Det er i denne oppgaven gjort en analyse av et eksisterende fjernvarmeanlegg på Oslo Lufthavn Gardermoen. Samtidig er det undersøkt muligheter for å implementere dyp geotermisk energi som grunnlast for anlegget. Et geotermisk design som kan møte noe av varmebehovet på anlegget er etablert. For å undersøke de miljømessige konsekvensene av et geotermisk system basert på Rock Energy sitt konsept, er det blitt utført en analyse basert på LCA metodikk.

Hafslund opererer de to varmesentralene som utgjør fjernvarmeanlegget på Gardermoen (Gardermoen varmesentral og en mobil sentral), hvorpå begge har blitt analysert for å fastslå potensialet for implementering av dyp geotermisk energi som grunnlast. Gardermoen varmesentral er koblet til flyplassen og området rundt. Denne sentralen er igjen koblet til den mobile sentralen, som ligger i nærheten av industriområdet sørøst for flyplassen. Basert på Hafslunds produksjonsdata fra februar 2011 til januar 2012, har effektvarighetskurven for de to eksisterende sentralene blitt etablert. Summerer man de to kurvene får man en topplast på 25,7 MW, og en årlig varmeproduksjon på 74 GWh. Den mobile sentralen utgjør kun 7,2% av den totale produksjonen per i dag.

Fremtidig varmebehov i Gardermoen-området er ventet å øke utover eksisterende kapasitet. Hafslund vurderer derfor å øke kapasiteten på begge fjernvarmesentralene. Utvidelsesplanene innebærer at varmesentralen må dekke en dimensjonerende effekt på 37,4 MW (24 MW per i dag), mens den mobile sentralen må økes til en dimensjonerende effekt på 15,2 MW (1,7 MW per i dag). Det er gjort en vurdering av hvor den geotermiske installasjonen eventuelt skal implementeres, og det er vurdert som det beste alternativet å implementere denne i den mobile sentralen. Den geotermiske varmen vil ha en kapasitet på 10 MW. Dette utgjør ca. 65% av det totale effektbehovet, og 90% av varmeproduksjonen til den mobile sentralen.

Den geotermiske installasjonen ble utformet ved hjelp av regnearket «Geocalc». De tekniske resultatene fra Geocalc har blitt brukt i en analyse av miljøkonsekvensene til systemet gjennom en såkalt livssyklusanalyse (LCA). LCA introduserer en måte å vurdere miljøkonsekvenser forbundet med alle faser i et produkts levetid fra vugge til grav.

Rapporten tar sikte på å gi normative resultater for miljøkonsekvensene av det geotermiske systemet på Gardermoen. Metoden gir mulighet til å kvantitativt sammenlikne resultatene med andre valg av energikilder for fjernvarme. Det er viktig å understreke at analysen gir en

oversikt over potensielle innvirkninger på miljøet, og ikke nødvendigvis de faktiske miljøkonsekvensene.

Systemet som er analysert er et 10 MW geotermisk anlegg med levetid på 30 år, og 5000 årlige driftstimer. Den funksjonelle enheten er kWh produsert fjernvarme. Analysen er basert på de viktigste medvirkende prosessene til konstruksjon, drift og avvikling av anlegget. Fjernvarmenettet er ikke inkludert i analysen, da dette allerede er installert på Gardermoen. Hvert bidrag i systemet har blitt systematisk vurdert. Det er imidlertid knyttet usikkerhet til enkelte av de innhentede dataene, hovedsakelig på grunn av motstridende informasjon på feltet. Informasjonen som anses å være mest usikker er energiforbruk til boring.

På grunn av dette er to ulike scenarioer for energibruk til boring etablert. Disse scenarioene er blitt simulert i en systemmodell i Excel som er basert på data og informasjon hentet inn fra eksisterende litteratur, databasen Ecoinvent, publiserte rapporter og personlig kommunikasjon med boreeksperter og spesialister innenfor de aktuelle fagområdene. Resultatene er vurdert etter følgende effektkategorier: Klimaendring, metall forbruk, fossil forbruk, forsuring av land ferskvanneutrofiering. Tre energikilder benyttet til boreoperasjonene er blitt evaluert; elektrisitet fra norsk nett, elektrisitet fra europeisk nett og diesel.

Kategorien klimaendring har vært i særlig fokus når simuleringene har blitt utført. Denne kategorien har stor spredning i resultatene, fra 0,9993 g CO2-ekvivalenter/kWh for beste scenario, til 23,6 g CO2-ekvivalenter/kWh for verste scenario. Som forventet konkluderer analysen med at elektrisitet fra norsk nett er det beste alternativet for energikilde til boring. For et eventuelt geotermisk system i Europa, viser resultatene at det ville være fordelaktig å bruke diesel som energiforsyning til boreoperasjonen i stedet for elektrisitet på det europeiske nettet, som gir en dobling i utslippet.

For metall forbruks-kategorien gir variasjon av energitilførsel til boring minst spredning i resultatene av alle kategorier. Dette er også den eneste kategorien der den norske elektrisitetsmiksen vil gi større konsekvenser enn dieselforbruk. Dette kan forklares ved at infrastrukturen knyttet til elektrisitetsdistribusjon er inkludert i analysen.

Resultatene av denne studien har blitt sammenliknet med andre LCA studier på fjernvarme med andre energikilder (avfallsforbrenning, biobrensel og termisk solenergi). Sammenlikningen viser at et geotermisk anlegg basert på Rock Energys konsept er en miljøvennlig energikilde til fjernvarme. Studiene som er blitt sammenliknet er imidlertid basert på varierende forutsetninger, og det kan derfor ikke trekkes en generalisert konklusjon basert på dette.

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Nomenclature

Latin symbols

A	Temperature gradient along borehole	[°C/m]
a	Annuity factor	[kr]
c_p	Heat capacity	[J/kgK]
d	Diameter	[m]
f	Friction factor	[-]
h	Heat transfer coefficient	[W/m^{2}K]
h_s	Heat transfer coefficient from wall of borehole to surrounding rock	[W/m^{2}K]
J_0	Bessel function	[-]
k	Thermal conductivity Absolute roughness	[W/mK]
L	Length	[m]
$\dot{m}$	Mass flow	[kg/s]
p	Pressure	[N/m^2]
Q	Energy demand/delivery	[kWh/yr]
q	Heat flux	[W/m^2]
q_s	Heat flux, borehole surface	[W/m^2]
r	Radius	[m]
r_0	Borehole radius	[m]
Re_d	Reynholds number	[-]
T	Temperature	[°C]
T_s	Temperature, borehole surface	[°C]
u	Integration variable	[-]
u	Velocity	[m/s]
Y_0	Bessel function	[-]

Greek symbols

α	Heat diffusivity	[m^2/s]
Δ	Differance	[-]
ρ	Density	[kg/m^3]
η	Coefficient of performance	[-]
μ	Dynamic viscosity	[Ns/m^2]

1 Introduction

1.1 Background

Focus on finding renewable low-carbon energy resources escalates as the focus on the environment and emissions of green-house gases increases. Geothermal energy is considered to have little CO_2-emissions and possesses an immense energy source. Rock Energy AS is a Norwegian company specializing in the development of deep geothermal energy in Norway, and they aim at becoming a leading geothermal company internationally.

Rock Energy has initiated an analysis of a district heating plant at Oslo Airport Gardermoen, operated by Hafslund. This plant is currently fired by biofuel, oil and electricity boilers, but it is planned an extension of the plant which might provide the opportunity for Rock Energy to implement deep geothermal energy at the site. Focus is to arrange for more environmental friendly energy production.

1.2 Objective

The overall objective of this thesis is to analyze the existing district heating plant at Gardermoen to find which opportunities are possible if implementation of geothermal energy becomes a reality.

In addition to the analysis of implementing geothermal energy, it is interesting to look at the overall environmental impact related to such systems. An analysis based on life cycle assessment (LCA) methodology will provide "life-cycle based" information on the conceptual geothermal system used in district heating. This will form a basis for evaluation of the environmental impact of such systems. This can in turn contribute to decide if this is a renewable energy source that should be considered for implementation in Norwegian district heating systems, and eventually be implemented in the international energy market. If the results of the analysis show environmental benefits for geothermal systems used in district heating, the report can contribute in decision-making for owners and committees controlling district heating development in the future.

1.3 Extent and Limitations

The level of detail of the existing district heating plant at Gardermoen includes the heating centrals and the grid. Due to certain information about the grid being considered as confidential information, this is not presented in the report. The grid dimensions are included, but the length of each pipeline is confidential information.

The focus of the work regarding geothermal energy is limited to utilization in district heating. No electricity generation is planned for this conceptual system. It addition, it is assumed that the achieved temperature gradient at the site is 25^{o}C/km, no further evaluation of this assumption is conducted.

A significant portion of the work of this study is to define the system boundary for what should be evaluated in the life cycle assessment, and at what level of detail each process should be implemented.

The system boundary is set to include the relevant processes for drilling the geothermal well system, surface equipment necessary for operation of the plant and closure of the wells. The district heating grid and peak load utility system for the plant is not included in the analysis. Furthermore, the drilling rig and disposal/recycling of equipment material at end of life are not included.

Information about the system is collected from relevant literature and experts in the field of study. The availability of data for the exact system is limited, as it is still at a conceptual level. The time available for the execution of the work will also be a limiting factor because the system at hand can be analyzed at a very detailed level. It has been necessary to make approaches and assumptions, based on a mix of empirical data from literature, qualitative information from Rock Energy, and drilling experts from industry and university.

To reduce uncertainty, it is advantageous to compare data from various sources. This has been done when possible.

Further evaluation of the extent of the study and quality of data is elaborated later in the report.

1.4 Report composition

The report commence with an introduction to district heating development in Norway the last four decades. Along with this the background of geothermal development in the same period is presented, as well as the key principles for utilization of geothermal energy. A short presentation of the differences between Rock Energy's concept and conventional concepts is included. Following this, a description of the framework for conducting an LCA is presented.

The remaining report is divided in to two main parts. First, the analysis of the district heating plant at Gardermoen is presented. It includes the present system and the enlargement plans. The possibility to implement a geothermal installation is included in this part of the report.

The last part of the report deals with the life cycle assessment of a geothermal system based on Rock Energy's conceptual design. A detailed description of the system analyzed is presented, together with limitations and uncertainties associated with the LCA. Assumptions underlying the calculations are also identified in this part of the report. Furthermore, the results of the analysis are presented. It has also been made comparisons to other literature.

Finally, the report's conclusion and recommendations for further work is presented.

2 Theory

2.1 Development of district heating

Up to 1975, there was a great commitment to water borne heating in all types of Norwegian buildings due to good access to affordable domestic heating oil. The 1973 oil crisis caused changes in this situation, by enlightening the vulnerability to reduced access to oil. This resulted in a transition to all-electric heating, especially for residential users.

From the middle of the 1970s, focus was put on enlarging the hydropower industry and infrastructure. The current Energy Act was however implemented the 1st of January 1991, which resulted in a stagnation of the hydropower expansion. At this time, Norwegian heating demand was entirely covered by the industry's electricity production [1].

Both population and energy use have increased since 1990, the Norwegian energy sector has therefore started importing electricity from neighboring countries. As the European electricity production is based on fossil, nuclear and renewable energy sources, import of electricity contributes to more emission of greenhouse gases. However, by sorting out the electricity independent consumption by implementing water borne heat, import of electricity can be minimized.

The availability and access to alternative energy resources for district heating has been under great development since the 1970s. Today, the use of waste heat, biofuels and natural gas are all implemented in district heating systems.

District heating systems are considered very energy flexible in terms of which energy carrier can be used. In existing district heating plants it is common that more than one energy carrier is used to cover the heating demand, thus one of the energy sources serves as base load, while the other covers the top load energy demand. This is due to demand for high temperatures in the system on the coldest days, but also in security of energy supply.

However, the district heating strategy for the future is pointing towards arranging for lower feed and return temperatures. This will contribute to increased flexibility of the systems, and a higher share of renewable energy sources can be utilized. Energy carriers in the low and mid temperature ranges, such as geothermal energy, will be able to be used directly without using an additional energy carrier.

2.2 Geothermal Energy

As the focus on the environment and emissions of greenhouse gases increases, so does the focus on finding renewable and low-carbon energy resources. Geothermal energy, generated and stored in the Earth, is an immense energy resource which can be utilized in an efficient way with the right technology. This energy is originated from the original formation of the planet 4,5 billion years ago, and from radioactive decay of isotopes in Earth's crust.

One can obtain both electricity and heat production with a low environmental impact. This thesis focuses on heat production for direct use only.

This section presents in short the concepts used for utilizing geothermal energy.

2.2.1 Hydrothermal- and Enhanced Geothermal Systems

One usually distinguishes between two types of systems when it comes to finding a suited method for utilizing geothermal energy. These are natural hydrothermal energy systems and Enhanced Geothermal Systems (EGS).

In the *hydrothermal system* the three main elements of a geothermal system, namely a heat source, reservoir and an energy carrier, are naturally present (located either in zones of volcanic activity or in proper sedimentary layers). Hot water can be produced by drilling in to a hot reservoir with sufficient natural permeability. The water produced from the reservoir will naturally be re-filled by precipitation. In some cases where this process is too slow to be able to keep up with the production rate, the produced water can be pumped back into the reservoir for re-heating after utilization in a power plant. The number of sites at which natural hydrothermal systems occur is limited. Therefore research activity has looked to the domain of so-called Hot Dry Rock (HDR) where the temperature gradient in the ground is high, but where the energy carrier must be provided artificially.

The *EGS system* differs from the hydrothermal system by not having natural permeability, thus the fluid for transporting the energy is not present. The heat source is present, and can thus serve as energy supply in direct use systems or in electricity production. Utilization of energy from so-called HDR systems has been a great field of research for several decades since high temperatures is encountered in vast areas of the earth. If the energy from such systems can be extracted in an economical feasible manner, geothermal energy will no longer be restricted to areas of high natural permeability. Engineered or Enhanced Geothermal Systems (EGS) refer to the utilization of these resources, where reservoirs have been constructed artificially to extract heat from the ground in areas with a previously impermeable body of HDR or in rock with naturally low permeability.

EGS systems are created by pumping high-pressure water into a specially drilled well so that the body of hot rock is *hydraulically fractured,* thus creating permeability in the hot dry rock [2]. From a worldwide perspective, the power production aspect of EGS has been given the highest priority of utilization alternatives, together with electricity production combined with direct use of heat.

During the last three to four decades, several attempts have been made to build Geothermal Power Plants based on EGS. Some have been more successful than others, and only a small portion of the projects have managed to produce economic amounts of power. These EGS concepts are multiple-well systems which exploit natural fractures and porosity in the bedrock as well as increasing the permeability by artificially stimulating the fractures between the wells. It was first thought that the stimulation of the bedrock was more or less independent of the natural fractures, but it has been concluded that the natural fractures and the stress regime in the rock is crucial for the development of the interconnectivity between the wells.

In the 1970's exploration at test sites such Fenton Hill (US) and Rosemanowes (UK) were the first conducted projects which tried to exploit an economic amount of hot water from a so-called Hot Dry Rock. The first phases of these projects were to create two boreholes, one for the injection well and one for the production well. Subsequently, interconnectivity between the wells was to be created by hydraulic fracturing. It was however discovered early that the fractures did not follow the path that was intended, and the desired connection was not established.

Following projects at test sites such as Hijori (Japan), Ogachi (Japan), Soultz (France) and Cooper Basin (Australia) took another approach to the problem. When interconnectivity had been shown to be hard to create between two existing wells, the solution was to drill *one* well, stimulate the reservoir and monitor the direction in which it grew. Thereby a second well was drilled into the existing reservoir, which now would give a path for the water to connect between the wells. The first barrier of finding a way to utilize geothermal energy from HDR was overcome, and it was proved beyond doubt that it was technically feasible to extract thermal energy from such rocks.

However, several problems arose also in later projects. Common for all the projects were the difficulties of find a suitable middle course for the injection pressure when stimulating the reservoirs. If pressure was too high, the reservoir would grow unintentionally and water losses increased. If the pressure was too low, the production rate would be too low to be of commercial interest. In cases where the reservoir would grow unintentionally short-circuiting became a problem, thus the water would not gain the available high temperature [3].

It was determined that with current technology, it was almost impossible to predict the stress field in the wellbore prior to drilling. Therefore it was acknowledged that the method of drilling, stimulating, mapping and then drilling in to the fractured area achieved the best connection between the injection and production wells.

The Cooper Basin project has proved that radiogenic granite can work as a geothermal reservoir. A number of practical experiences have been gained related to reservoir construction and drilling. The project indicates that it is possible to establish multiple-borehole systems (several production- and injection wells per reservoir) when the reservoir has a horizontal development. This can upgrade the systems production rate and make it competitive to other technologies and energy sources.

Cooper Basin is an ongoing project with a plan to commission a 1MW pilot plant in the first quarter of 2012, and thereby produce Australia's first EGS power[4].

At Soultz the primary circuit has the intention to heat the injected water at depths of 4500-5000 meters, the temperature at this depth is about 200°C. Today the plant produces regularly with an electrical production capacity of 1,5 MW, through an Organic Rankine Cycle (ORC) [5].

2.2.2 Rock Energy Concept

The Hot Dry Rock (HDR) technology utilizes heat in the rock within Earth's crust. The rock is hot and dry, and permeability for water to penetrate the rock must therefore be artificially constructed.

Rock Energy is a Norwegian company with a patented technology for drilling deep geothermal wells for exploitation of geothermal energy from HDR. Their technology is based on drilling technology from the oil and gas industry, which has made it possible to drill in the horizontal direction sub-surface of the Earth. This technology differs from the traditional EGS systems, as it secures inter-well connectivity without fracturing the rock between the wells. Instead of hydraulically fracturing the rock to create permeability, the patented technology of Rock Energy is based on drilling a sub-surface heat exchanger of tubes in the HDR. A conceptual model is presented in Figure 2.1.

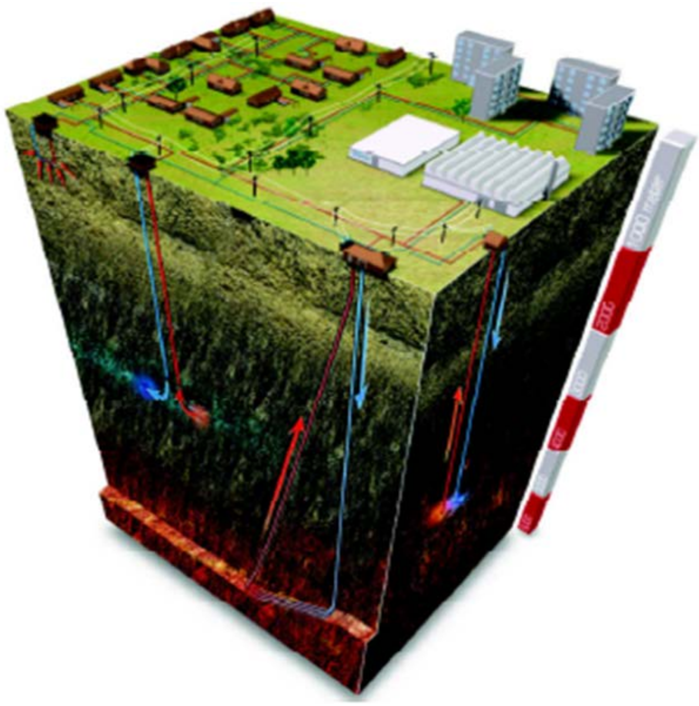


Figure 2.1 - Rock Energy's sub-surface heat exchanger

Exploitation of geothermal energy based on Rock Energy's technology is therefore only limited by the accessible depth modern technology can reach and the cost of extraction. Fluctuation of temperature gradient can however complicate the temperature projections, as there are vast areas in which the temperature gradient is far from the average value. The main focus of drilling for geothermal energy is therefore to find a suitable site where the temperature is sufficiently high, together with a relatively high heat demand close to the site.

The main advantage of Rock Energy's concept is that it secures connectivity between the injection and production well. This has been one of the greatest challenges for traditional EGS concepts worldwide. At several EGS sites the problems that emerged were both that injected water was lost to the reservoir, or the water short-circuited and thereby did not gain the desired temperature. In addition to the challenges regarding connectivity between the wells of traditional EGS concepts, seismic events have been provoked by hydraulic fracturing. In some cases this has led to termination of the projects, due to safety aspects.

Rock Energy's concept involves a considerable high amount of drilling compared to traditional EGS concepts. This implies that this concept is costly in the constructional phase of the projects, and confidence in reaching a sufficiently high temperature is thereby of great importance.

However, the sub-surface heat exchanger concept of Rock Energy is predictable once the system has been constructed. Also, the drilling technology is feasible and has been verified by off-shore drilling technology for several decades.

The Rock Energy concept is in this report the basis for further investigation of the feasibility of geothermal energy utilization at Oslo Airport Gardermoen.

2.3 LCA

The definition of an environmental life cycle assessment is according to ISO 14040 "a compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle". In this chapter the main principles and methods for conducting an LCA are presented, based on the standard [6],[7].

2.3.1 Methological Framework (ISO)

The purpose of an LCA is to identify all processes in a product's or services' life cycle. This comprises the extraction of natural resources, through production to disposal or re-use. In addition, identification of all related mass flows and energy flows involved, as well as emissions. Subsequently the resources and emissions will be classified according to which effect it has on environmental categories [8].

The focus of an LCA is the environmental aspects related to a products life. Economic and social factors are usually not covered by an LCA [7]. However, economic knowledge about the product can be of assistance during the assessment. Usually, the parts of the process with the heaviest expenses are likely the same processes which will have the highest environmental impact.

LCA methodology uses an iterative technique, meaning that the results developed throughout an LCA are dependent on the previous results [7]. It is therefore necessary when conducting an LCA to establish a set of data necessary to describe the system, and subsequently validate if the data is suitable for this purpose. If the data are suitable or can be found suitable on reasonable premises, the data is entered into the data set for further use. If the data is not suitable, one needs to go back and conduct further search for data and information.

An LCA is structured around a *functional unit*. All analysis performed within an LCA study must be presented in relation to the functional unit [7]. In the case of study of heat delivering facilities, such as district heating (e.g. with geothermal base load), the functional unit appropriate is MJ. All emissions and environmental effects are being quantified per unit of energy (MJ) produced.

An LCA is organized in the following main phases, also shown in Figure 2.2:

- The goal and scope definition
- Life cycle inventory analysis
- Impact assessment
- Interpretation

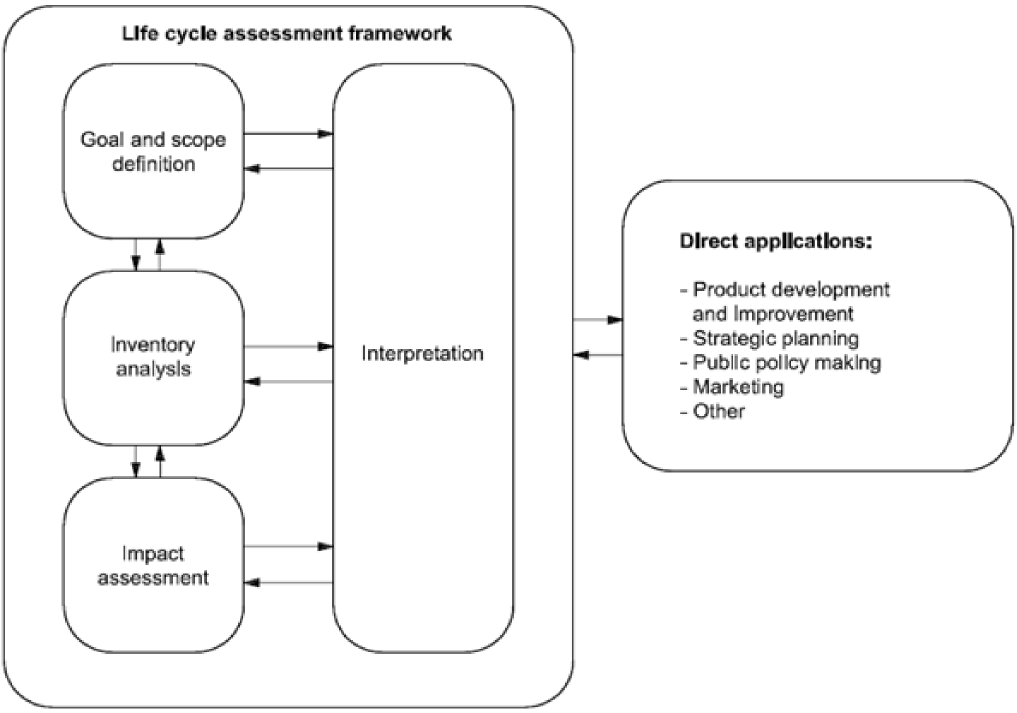


Figure 2.2 – Framework of the life cycle assessment [7]

When an LCA is conducted, it should follow the standards NS-EN ISO 14040:2006 and NS-EN ISO 14044:2006. This will secure the reliability of the report.

A presentation of the phases will follow next, focusing on general content. Specified adaption for the system described in this report will be discussed in chapter 5.

2.3.2 Goal and Scope Definition

The establishment of the goal and scope of the LCA is determining for the methodological choices for conducting the study [8].

The goal should comprise of the following [7]:

- The intended application of the study
- Reasons for conducting the study
- Intended audience
- Whether the results are to be used in comparative statements which are published

The scope must be defined in relation to the goal of the study, meaning that the level of detail should reflect the goal of the LCA. The scope will therefore be determining for the product system to be studied, the functional unit and suitable system boundaries, presented next.

The Product System

The product system to be studied needs to be defined at a detailed level. This is especially important for comparative studies. The different objects of comparison must be coupled together by defining an appropriate functional unit so that comparability is ensured. Also, the systems boundaries, quality of data, allocation procedures and effect evaluation must be equal in a comparative study. Differences between the systems should be identified and reported [7].

The functional Unit

The functional unit's primary purpose is to define a reference to which the inputs and outputs are related [7]. The functional unit is therefore a way of securing that the comparativeness in LCA studies are done on a general foundation. The functional unit must reflect the goal of the study [8]. Omissions from the systems function shall be described and documented in the report [7].

The System Boundary

LCA is conducted by defining product systems as models that describe the key elements of physical systems. The system boundary defines the unit processes to be included in the system [7]. The system boundary is based on the purpose of the study, intended application and audience, data and cost constraints. The criteria that are used to decide what should be included within the system boundary shall be identified and described. Leaving out parts of the system is only appropriate when the result is not affected by this [6]. Several life cycle stages should be taken into consideration, for example [7]:

- Acquisition of raw materials
- Distribution/transportation
- Production and use of fuels, electricity and heat
- Use and maintenance of products

- Disposal of process wastes and products
- Recovery of used products (reuse, recycling, energy recovery)

It is an advantage to organize the system in a foreground and background system. This will easier let one determine which processes which can be changed, and what the effect of this will be. More on background and foreground systems will be presented in section 5.7.1.

It is common to set a lower limit based on mass, energy or environmental effect for what is included within the system boundary. This is done to avoid time consuming work in treating insignificant parts of the system, which will not affect the results to any great extent.

2.3.3 Life cycle inventory (LCI)

Inventory analysis involves data collection and calculation procedures to quantify relevant inputs and outputs of a production system [7]. This phase of an LCA is usually the most time consuming. Usually 80 % of the data can be found in databases. The other 20 % is particular or specialized product system information and must be quantified by research from the industry or similar.

The inventory analysis uses an iterative technique, as shown in Figure 2.3. As data are collected and more is learned about the system, new data requirements or limitations may be identified that require a change in the data collection procedures so that the goal of the study will still be met [7].

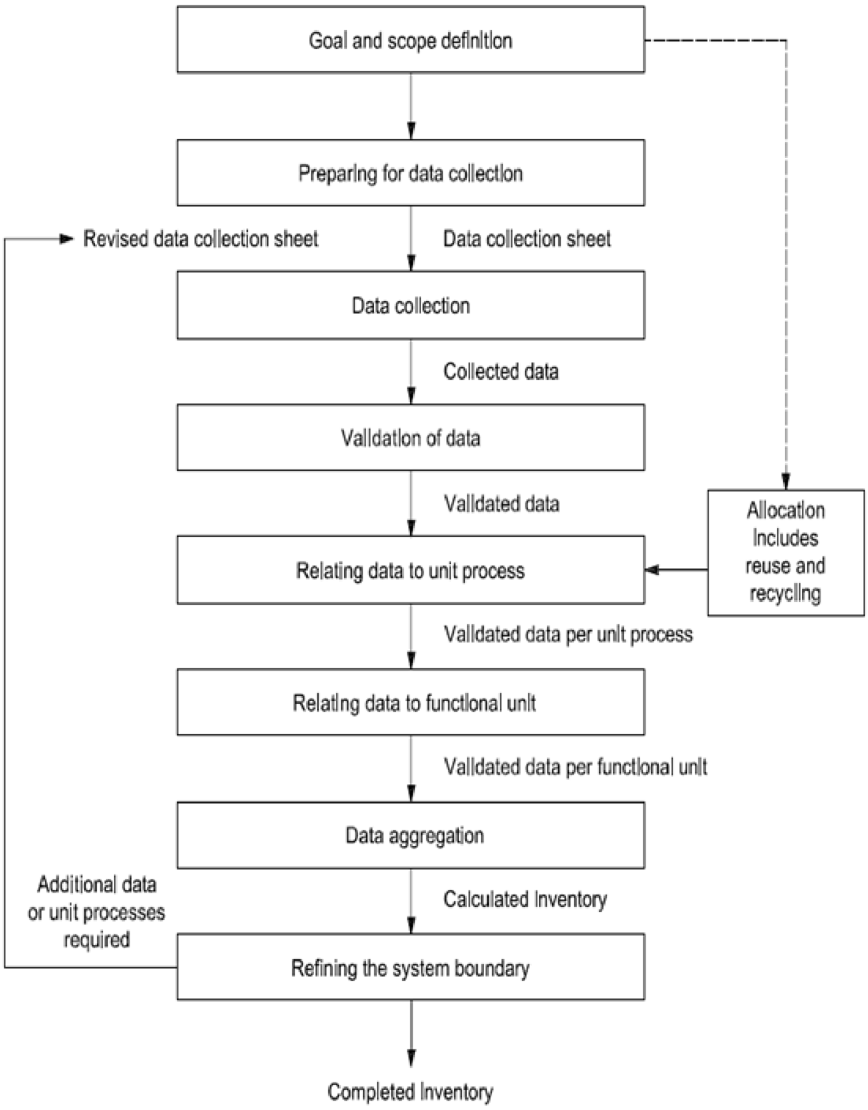


Figure 2.3 – Structure of LCI

The data within the system boundary can be classified according to different categories, for example for inputs could consist of energy inputs, raw material inputs, or ancillary inputs. For the products one could have main products, co-products, and waste. Emissions can be divided into several categories, some of which are emissions to air, discharge to water and soil and so on [7].

2.3.4 Life cycle impact assessment (LCIA)

The impact assessment phase of an LCA is aimed at evaluating the significance of potential environmental impacts using the LCI results. This process involves associating the data from the LCI with specific environmental impact categories and category indicators [7].

One may have to revise the results in the impact assessment phase, to make sure the target of the LCA study have been met. Goal and scope modification may be necessary if it is indicated that these cannot be met [7].

Transparency is important in the impact assessment to ensure subjectivity is not influencing the results. Assumptions should be clearly described and reported [7].

According to ISO 14044 the LCIA is comprised by three major elements:

- Selection of impact categories, category indicators and characterization models
- Assignment of LCI results to the selected impact categories (classification)
- Calculation of category indicator results (characterization)

2.3.5 Life Cycle Interpretation

In this phase the results from the life cycle inventory analysis and impact assessment are seen in context. The interpretations should deliver results that are consistent with the defined goal and scope of the LCA study. Conclusions should be reached, limitations should be explained and provide recommendations [7].

Conclusions, which have quality assurance with regard to the goal and scope of the LCA study, may be presented as recommendation to decision-makers. It should however be clear that the results from the LCA study point out potential environmental effects and that the results do not predict actual environmental effects, exceeding of thresholds, safety margins or risks [7].

The interpretation of the results should also include an evaluation of to what degree the system functions, the functional unit and the system boundary is satisfying. Possible limitations revealed by evaluation of the data quality or sensitivity analysis should also be covered [6].

2.3.6 Tools/databases

Data based tools for conducting LCA studies have been developed. Usually the task of collecting and sorting data is challenging and time consuming, and the use of analysis tools will provide efficiency to the process.

A number of databases containing information about input and output factors for chosen processes are meant for covering the background system. These predefined processes must be adapted to the processes in the system being evaluated. The degree of quality and up to date fit varies between the data bases.

The selection of database is based on the goal and scope of the particular study. It is preferable to stick to one database as this secures that the processes are established on an equal ground of consistency with corresponding system boundaries and extent.

In this study Ecoinvent is chosen as the database for collecting background information, which has developed to be the most common and trusting LCA database for European purposes. Ecoinvent's foundation builds on the ETH-ESU 96 database, which was established in 1996 as a joint effort between the Swiss Federal Institute of Technology, Zurich (ETHZ) and the consulting company ESU. Ecoinvent was compiled as a joint project between institutions as; ETHZ, Paul Scherrer Institute (PSI), Swiss Federal Laboratories for Materials Testing and Research (EMPA) and others [9]. The database contains useful data within a wide range of process categories such as energy supply, fuels, heat production, electricity generation, plastics, paper and board, waste treatment services, metals, wood, building materials and transportation [9].

2.3.7 Critical review of life cycle assessments

Quantitative information is well suited for generalization based on systematic analysis. The chosen method makes it possible to quantitatively compare sources for heat generation in a district heating system. It is however important to emphasize that the results of an LCA provides an "overview" of potential environmental effects a product system can lead to, and not necessarily what will actually be the result of production.

An LCA is a data-intensive procedure. Uncertainties may therefore be of great importance if one is not critical to the data used for input. The conclusion's validity is therefore dependent on the validity of the input. If there are considerable uncertainties related to the input data, analyzes should be conducted to uncover the system's sensitivity of these uncertainties.

3 Analysis of the Energy System at Oslo Airport Gardermoen

In this chapter a conducted analysis of the district heating plant at Gardermoen is presented. The plant consists of two centrals, which throughout this report are referred to as "the heating central" and "the mobile heating central." In the first section, emphasize has been on the existing district heating plant at Gardermoen, including the two centrals and the belonging distribution network. Based on Hafslund's registered data on load and production from February 2011 to January 2012, a duration curve for the load has been constructed. The pattern of this curve has also been the foundation for establishing a new duration curve for the planned expansion of the plant. The dimensions of the grid have been evaluated to determine the grid's ability to meet the expansion.

When examinations of the present load and production requirements have been conducted, the heating central and the mobile heating central have not been considered separately. This is due to a relatively small heat production related to the present mobile heating central.

However, the extensions that are planned to be completed by 2022 will lead to a higher installed capacity and heat production for the mobile heating central. The two centrals have for this part been considered separately.

3.1 Analysis of Existing District Heating Plant at Gardermoen

The area of Oslo Airport Gardermoen and the industrial estate south-east of the airport are located in Ullensaker and Nannestad municipality in Akershus. A district heating network that consists of two heating centrals is connected to this area, and is operated by Hafslund. The data used in this analysis were gathered during a visit to the plant the 22nd of February, and consist of Hafslund's registered data on load and production from February 2011 to January 2012.

3.1.1 Description of the heating central and the mobile heating central

Appendix 1 shows a map of the district heating grid at Gardermoen. The heating central is located west of the extended area surrounding the airport. This central produces heat that is distributed to Oslo Airport Gardermoen (OSL) and its belonging runways, and to the industry and hotel area west of OSL.

Figure 3.1 gives an overview of the heating central at present.

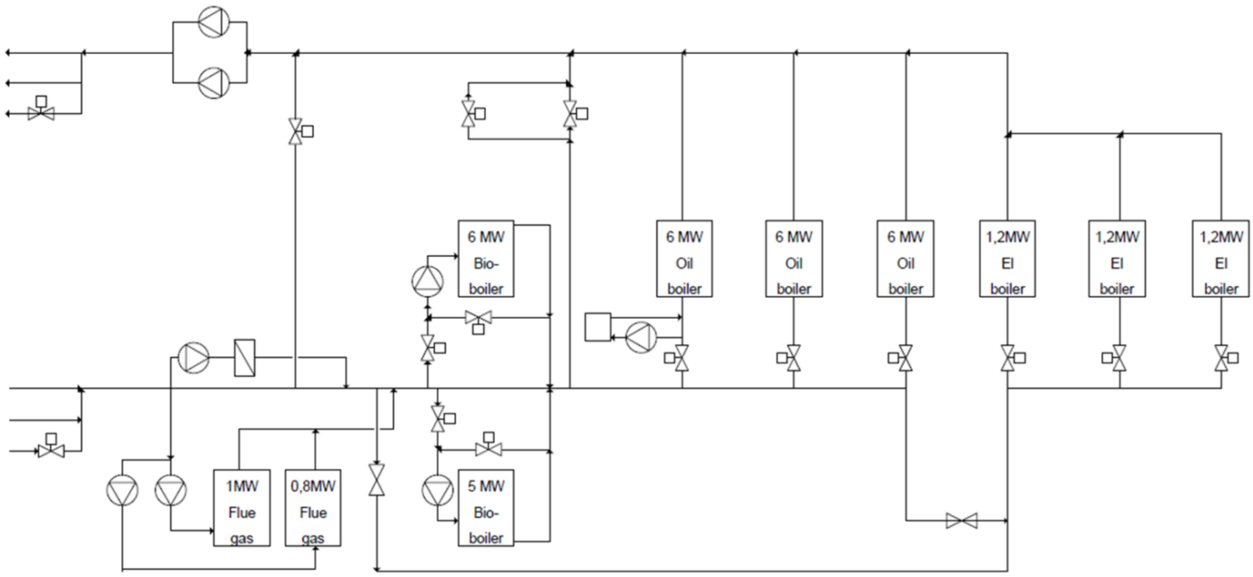


Figure 3.1 – Overview of the heating central's installations

The heating central consists in total of two flue gas condensers and eight boilers connected in series. Two bio-fuel boilers with an installed load of 5 and 6 MW, constitute the base load of the central, which cover 65-70% of the total energy production of the plant. Each of these boilers are connected to a 1 MW flue gas condenser, both installed at the entrance of the plant, providing the first temperature lift of the cold return water. In addition, the central consists of three oil boilers, each with a capacity of 8 MW, and three electrical boilers with a capacity of 1,2 MW each. These constitute the peak load of the central. Which of the boilers being used at a given time depend on the market price for oil and electricity.

In total the heating central has a capacity of 40,6 MW, and summarized it consists of the following installations:

- One bio-fuel boiler with an installed load of 5 MW + 1 MW flue gas condensation
- One bio-fuel boiler with installed load of 6 MW + 1 MW flue gas condensation
- Three oil boilers with a load of 8 MW each, giving a total load of 24 MW
- Three electrical boilers with a load of 1,2 MW each, giving a total load of 3,6 MW

The mobile heating central is situated east of the airport area, providing heat to the industry located at the industrial estate close to the airport (map Appendix A). Figure 3.2 shows an overview of the central.

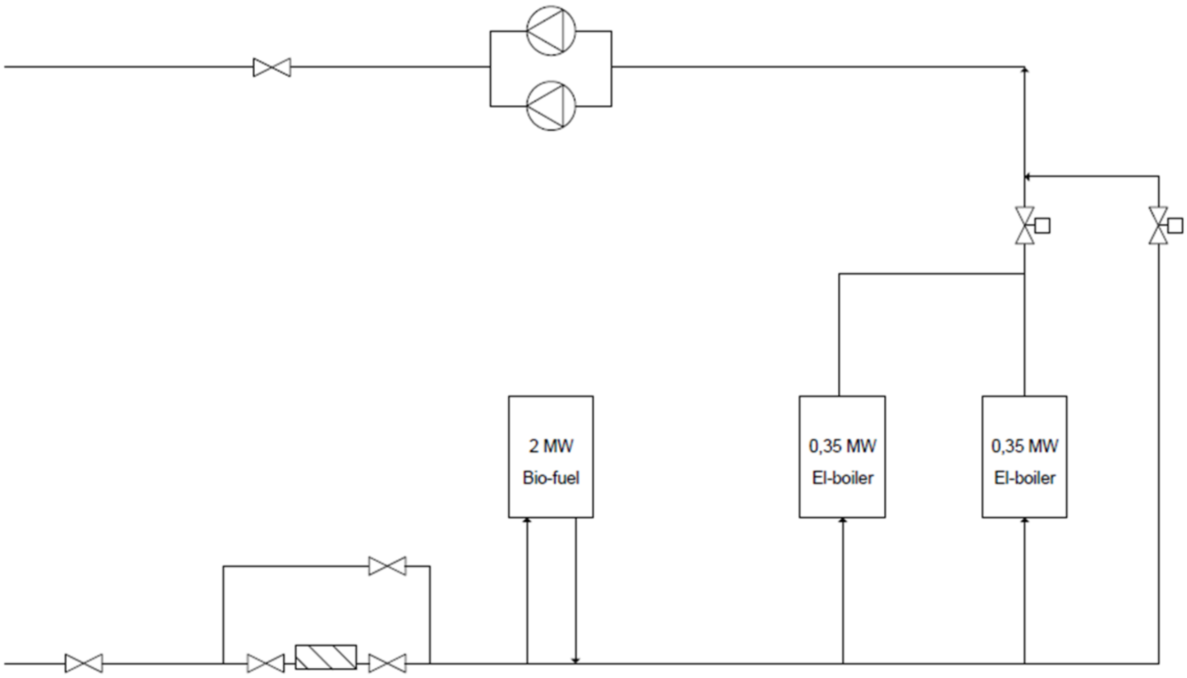


Figure 3.2 – Overview of the mobile heating central's installations

The mobile heating central consists of one bio-fuel boiler with a capacity of 2 MW. In addition, there are two electrical boilers installed, each with a capacity of 0,35 MW. These two are meant as a back-up solution and are not in use as long as the bio-fuel boiler is in use.

3.1.2 Operation of the plant

The fundamental heat output control principle used for the two heating centrals at Gardermoen is control of mass flow rate. However, temperature is coarsely adjusted to summer and winter energy demand.

During the summertime, when energy demand is low, the feed temperature lies mainly in the range of 90-95^{o}C. This is sufficient for delivering heat for hot tap water, and occasionally heating or ventilation. During the winter, when the energy demand increases considerably, the feed water temperature is increased to 100-110^{o}C.

The regulation system is controlled by a minimum pressure difference on the feed and return flows. The pressure distribution through the piping system will look like the illustration presented in Figure 3.3.

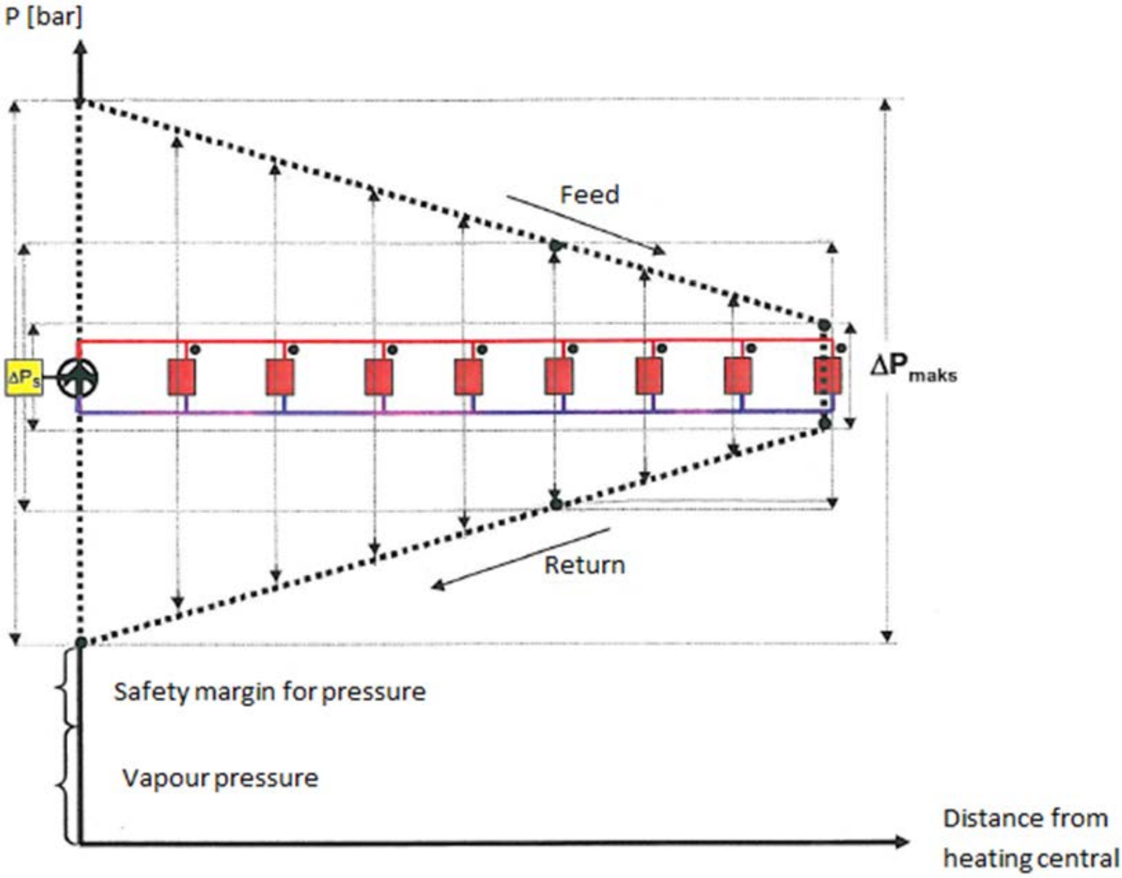


Figure 3.3 – Pressure distribution in district heating network [1]

The declining line is the pressure distribution for maximum load, and will be close to linear. The pump must provide the required pressure, ΔP_S, which applies to the pressure drop throughout the system to the last subscriber in the grid.

It is important to keep the pressure at a certain confidence level to avoid any formation of vapor in the system. For high to medium temperature systems, such as the one at Gardermoen, the temperature can reach 120°C. At this temperature the vapor pressure is 2 ATA[1]. One must therefore at all times keep the pressure at a safety margin above this level.

[1] Unit of absolute pressure equal to one atmosphere

3.1.3 Description of the grid

Figure 3.4 shows the relative distribution of the energy demand for each of the costumers in the grid. The two largest customers are OSL Heating Central and Scandinavian Airline System which together account for half of the demand.

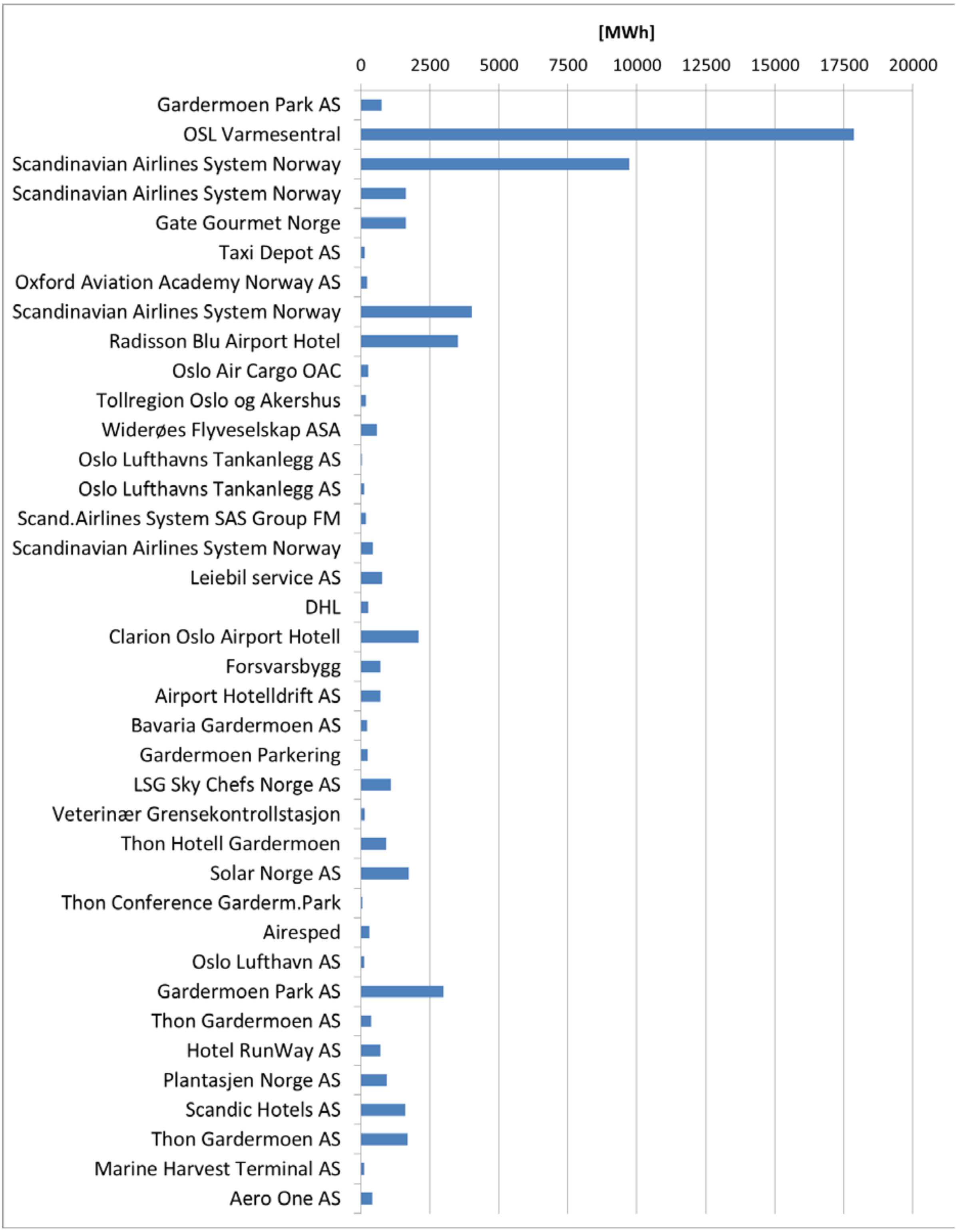


Figure 3.4 – Customers' energy consumption for 2010

The mobile heating central is connected to the heating central by a connecting pipeline. It has not been possible to access data regarding the mobile heating central's customers. The load and energy production have nevertheless been taken into account for the analysis of the total energy production and design load.

The distribution system for both the heating central and the mobile heating central, follow the basic structure of a typical "star-shaped" system, as illustrated in Figure 3.5. The lines in the figure symbolize both feed pipes distributing the hot water to the costumers and the pipes returning the cooled water.

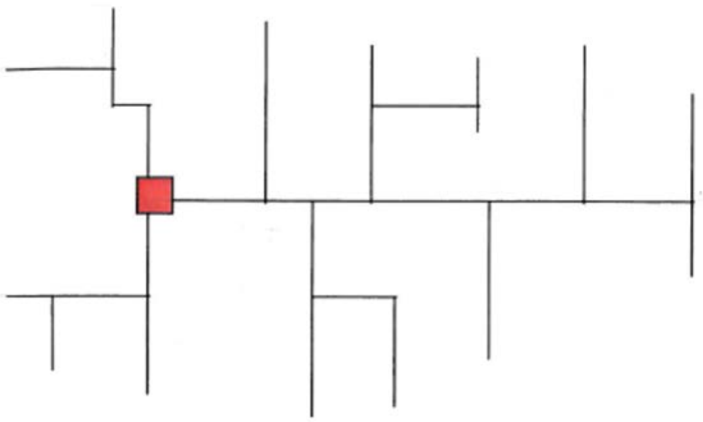


Figure 3.5 - Basic structure of a "star-shaped"system [1]

The water supply to the customer in this type of system is characterized by only one possible route. This structure is often used for smaller systems, or in systems where chances of extensions are present.

3.1.4 Pipes and dimensions

When distributing hot water over distances, heat loss will occur. The range of loss can however be limited. The main purpose of a piping system is to minimize the heat loss, and thus maintain the high water temperature. Pre-insulated pipes are widely used for district heating and hot water supply in Europe. The pipes consist of a steel pipe, an insulating layer, and an outer casing [1].

The insulating layer usually consists of a polyurethane foam, with a thermal conductivity k=0.033-0.024 W/mK. The outer casing is made by a plastic material, usually high-density polyethylene (HDPE) [10].

Pre-insulated pipes are prefabricated, and have been the dominating solution in district heating systems in the latest decade. Most commonly used are single insulated pipes, but more recently in Europe it is becoming popular to use two pipes insulated within the same casing.

The pipe dimensions used in the distribution network at Gardermoen are presented in Table 3.1.

Table 3.1 – Pipe dimensions for the grid connected to heating- and mobile heating central

Heating central		Mobile central	
Inner diameter [mm]	Outer diameter [mm]	Inner diameter [mm]	Outer diameter [mm]
300	500	300	500
250	400	250	450
200	315	200	355
150	250	150	280
125	250	125	250
125	225	125	225
100	200	100	315
80	160	100	225
65	140	80	180
50	125	65	160
-	-	50	140

The connecting pipe between the two centrals has an inner diameter of 300mm. All other pipes exiting the centrals have an inner diameter of 250mm. The pipe dimensions' respective length has not been available.

Extension of the two centrals will be evaluated later in this chapter. The grid and its dimensions will be of particular interest due to the importance of determining whether a higher design load, thus mass flow (given that the original water temperatures remain the same), will cause excessive pressure drop in the distribution network, exceeding the recommended limits.

3.1.5 Load and production

For further analysis of the potential of a geothermal installation, the thermal energy output for one year has been collected and reviewed. The data consist of logs providing load and production on a daily basis. Logs are only registered for the heating central.

From February 2011 to January 2012, the total thermal production for the heating central was 58 GWh. The limited information gathered for the mobile heating central, indicate a thermal production of approximately 4,5 GWh. This production represent 7,2% of the production at the heating central. After consultation with Øyvind Nilsen at Hafslund [11], a 7,2% increase in the heating central's registered load has been added, assuming that the pattern of use is approximately the same for the two centrals.

As it appears from Figure 3.6, the total maximum load over the year has varied from 2,5 MW during summer months to 26 MW during the winter months. As the two centrals together have a total capacity of 43,3 MW, the peak load of 26 MW constitute for only 60% of the installed capacity.

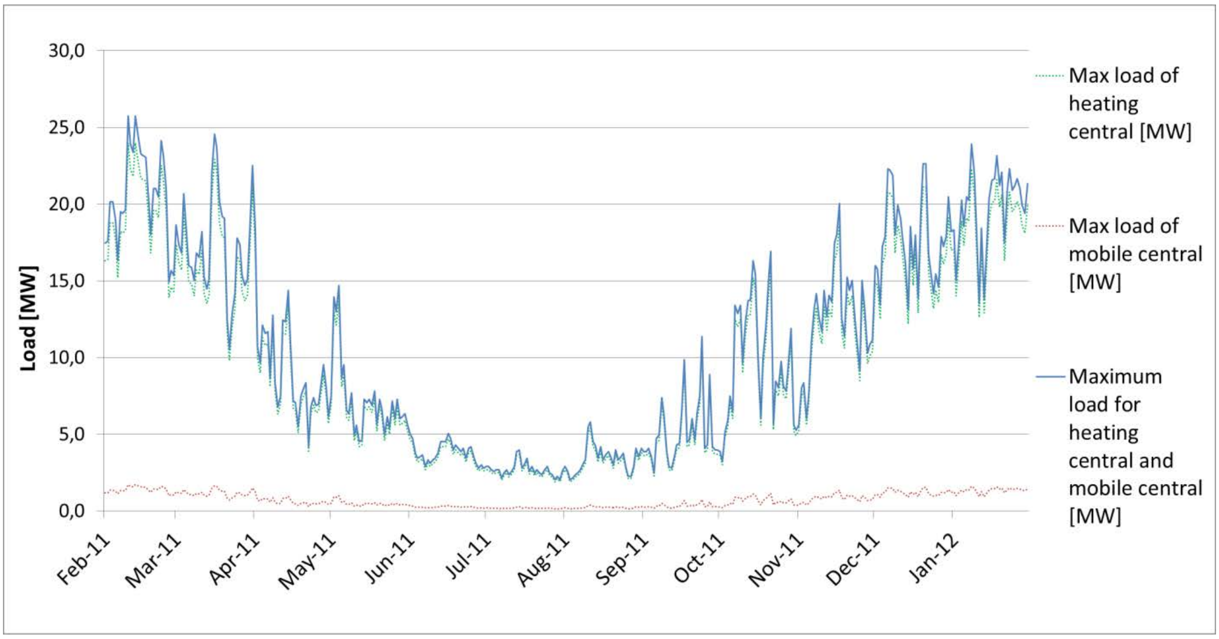


Figure 3.6 – Max load registered from February 2011 to January 2012

The blue curve represents the total maximum load for both of the centrals, while the green and red "dashed" curves symbolize the distribution of the heating central and mobile heating central, respectively.

The mean load is not registered in the log available for the heating central. The mean load has therefore been found by dividing the thermal production by the hours of operation. As for the maximum load, a 7,2% increase has been added to the curve, providing a mean load curve for the joint system. The result can be seen in Figure 3.7.

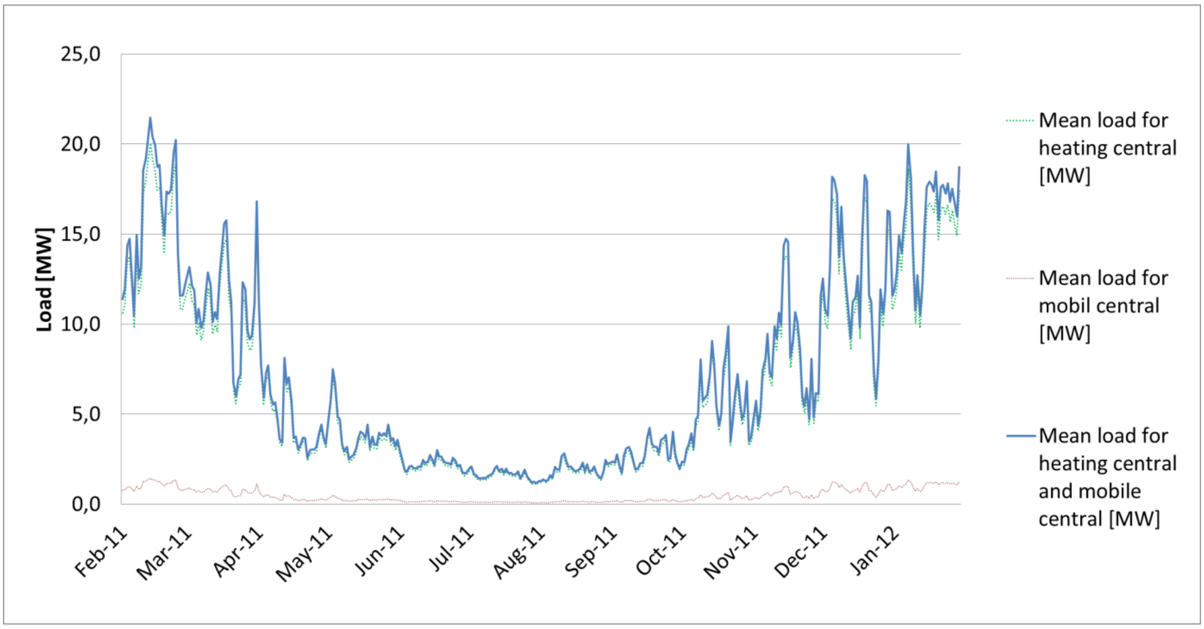


Figure 3.7 – Mean load registered from February 2011 to January 2012

By sorting the data provided for the mean load per day, from the highest value to the lower, the load duration curve for the joint system can be presented.

3.1.6 Duration curve for required load at Gardermoen

To get a better understanding of the heat demand of the customers connected to Hafslund's heating central and mobile heating central, it is important to study the load duration curve for the system throughout one year. The maximum load one might achieve in any year of operation is the design load of the whole system. In this section the duration curve for the present system (including both the heating central and the mobile heating central) is presented.

Duration curve for the heating central and the mobile heating central

Based on the mean load presented in Figure 3.7, Figure 3.8 shows the obtained duration curve.

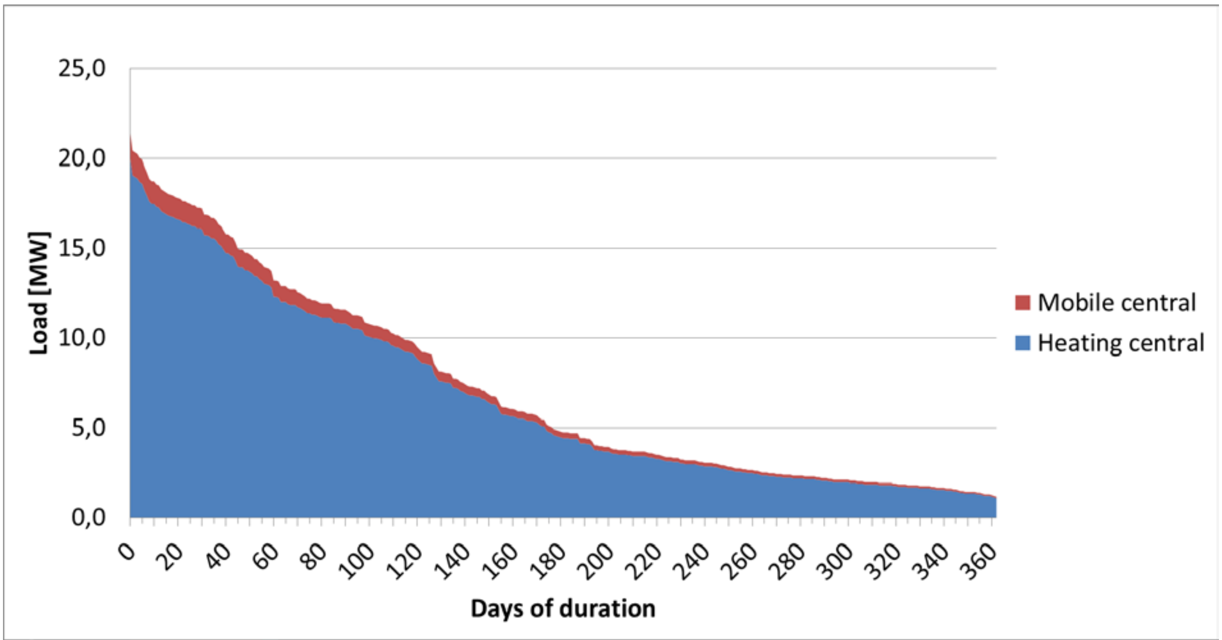


Figure 3.8 – Duration curve based on mean load

The blue curve represents the duration curve for the heating central's mean load over one year of operation, while the red curve represents the duration of the mobile heating central's mean load. As mentioned, this curve is estimated to represent 7,2% of the heating central's load. The area below the two curves represent the heat production for the heating central and the mobile heating central, respectively. The area of the red and the blue curve represents therefore the total heat production of the joint system.

One of the drawbacks of a duration curve based on the mean load over the year, is that the maximum load and hence the design load does not appear. Figure 3.9 shows for comparison also the duration curve based on the registered maximum load, presented in Figure 3.6.

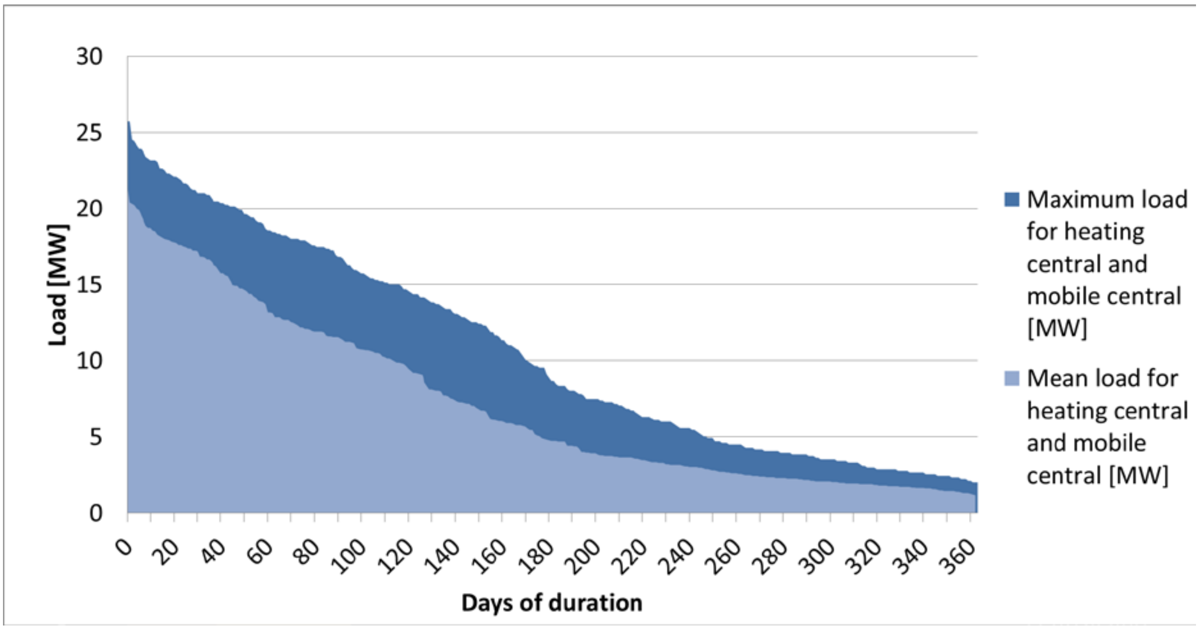


Figure 3.9 – Duration curve based on mean and max load

The lower curve represents the joint system of Figure 3.8, while the upper curve represents the duration of the maximum load.

The design load that emerges from the duration curve for maximum loads, and heat production corresponding to the area below the mean load duration curve, forms the basis for further analysis and dimensioning. Table 3.2 summarizes the values that this represents.

Table 3.2- Registered load and production for heating and mobile heating central

Design load [MW], feb.2011-jan.2012	Production [GWh], feb.2011-jan.2012
25,7	62,5

It has for the previous calculations in this chapter been assumed that data collected for February 2011 to January 2012 will follow the same trend as for an average year. However, the annual data for 2011 will somewhat be lower than what is a typical distribution for the energy requirements, due to higher temperatures than normal during the winter 2011. This emerges from Figure 3.10, where the outdoor temperatures registered from February 2011 to January 2012 are plotted with the mean temperatures registered for Gardermoen from 1961 to 1990 [12].

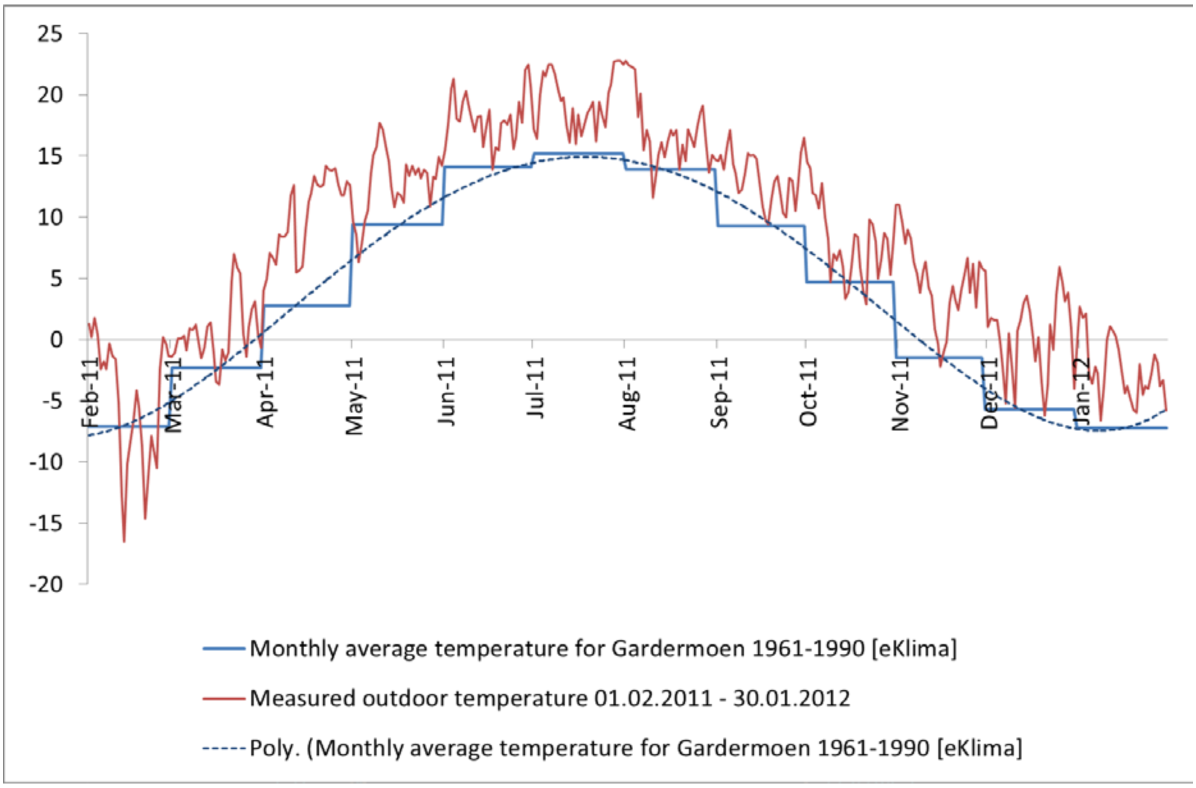


Figure 3.10 – Measured outdoor temperature Feb.2011-Jan.2012

The curves show the measured outdoor temperature of 2011 exceeding the monthly average temperature, which indicate that the total production estimated to be 62,5 GWh, is lower than for an average year. This is corrected for in the next section.

Correction for Number of Heating Degree Days

A higher outdoor temperature than normal throughout 2011, results in a lower registered production during this year. Table 3.3 shows the production registered for the joint system the last three years.

Table 3.3 – Registered production, 2009 – 2010

Year	Registered production 2009-2012
feb.2011-jan.2012	62,5 GWh
2010	77,4 GWh
2009	68,5 GWh

As can be observed, the total production registered for 2009 and 2010 were 10% and 24% higher than for 2011, respectively. An estimated production for a general year of operation can be presented if corrections for number of heating degree days (HDD) are made.

The number of HDD is a measure of the amount of time, and by how much, the average temperature on a particular day is below the indoor temperature. The indoor temperature used for this purpose is by standard set to 17°C. This means that one degree day is a 24-hour period with a difference between the indoor and outdoor temperature of 1°C [1].

The energy production is corrected as in Equation 3.1

$$Corrected\ energy\ prod. = registered\ production * \frac{mean\ no.of\ degree\ days}{measured\ no.of\ degree\ days} \quad (3.1)$$

Data collected from eKlima [12], which provide weather and climate data from the Norwegian Meteorological Institute are presented in Table 3.4.

Table 3.4 – Mean and measured number of heating degree days

Mean no. of degree days at Gardermoen	Measured no. of degree days at Gardermoen
4820,2	4069,2

The mean number of degree days is based on data registered from 1961 to 1990, while the measured number of degree days is based on measured data registered from 1st of February, 2011 to 31st of January, 2012.

Equation 3.2, gives the corrected energy demand:

$$Corrected\ energy\ prod. = 62{,}5\ GWh * \frac{4820{,}2}{4069{,}2} = 74\ GWh \quad (3.2)$$

Compared to the registered production presented in Table 3.3, a corrected energy production of 74 GWh differs less for the production registered in 2009 and 2010, than for the production of 2011.

3.2 Extension of the two centrals

The map in Figure 3.11 shows a situation map of the heating central connected to Oslo Airport Gardermoen, and the mobile heating central connected to the industrial estate, south-east of the airport.

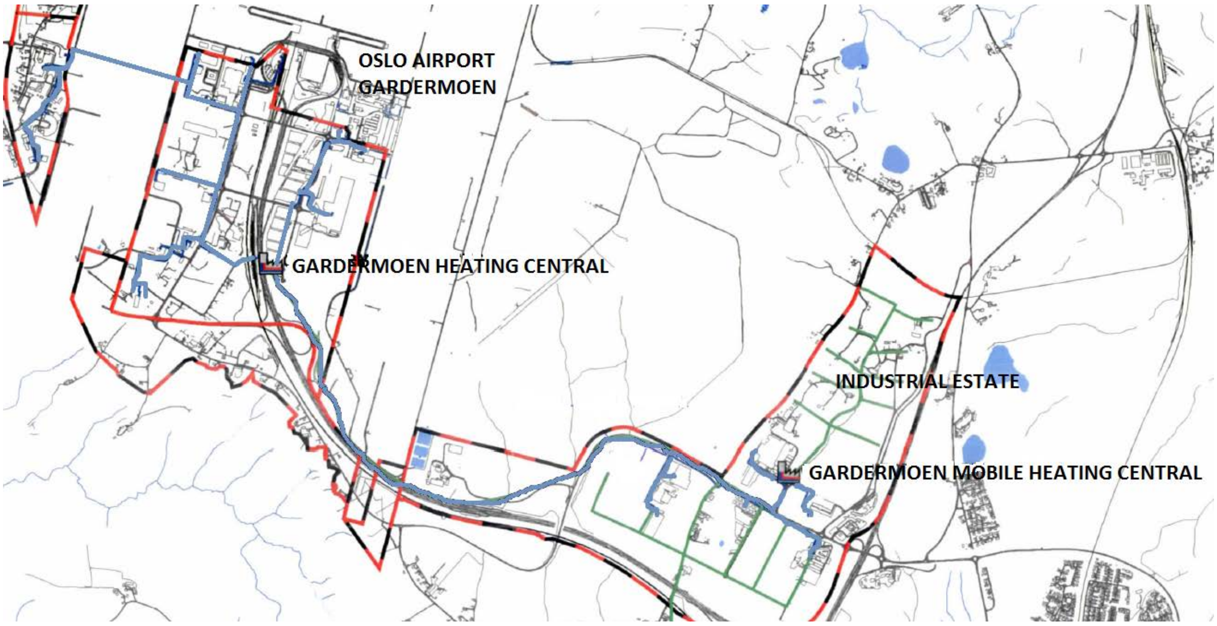


Figure 3.11 – Map of Oslo Airport Gardermoen and the industrial estate

The blue line represents the present grid that distributes heat to the costumers, and connects the two centrals.

Future heat demand in the Gardermoen area is expected to increase beyond existing level. Hafslund is therefore considering to increase the capacity of both their district heating centrals. Curves for the estimated load and expected energy production from 2012 to 2022 are illustrated in Figure 3.12 and Figure 3.13.

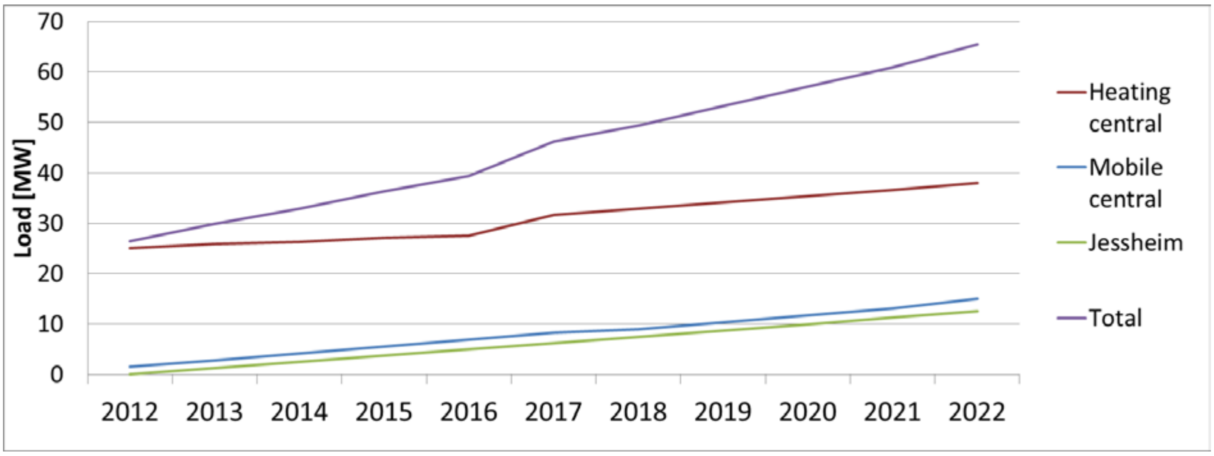


Figure 3.12 – Expected design load [MW], 2012 – 2022

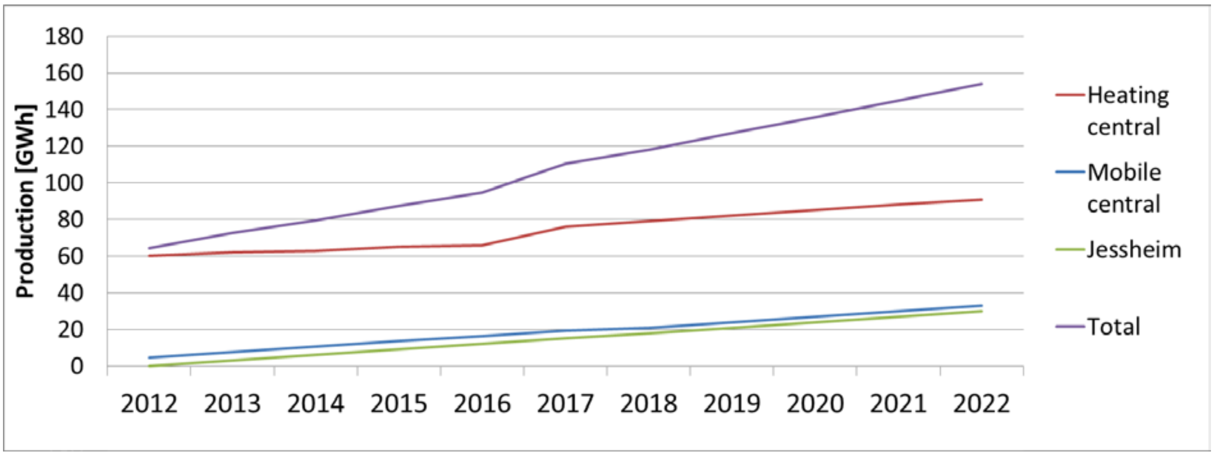


Figure 3.13 – Expected heat production [GWh], 2012 – 2022

The red curve shows the projected increase in load and heat demand related to the heating central, and comprises smaller extensions of the existing network north and west of the central. The production is expected to increase from the present value of 60 GWh (closer to 65 GWh, as the registered production in Table 3.3 shows), to a value of 90 GWh within 2022. The design load is expected to rise towards 40 MW, within the same period.

The blue curve applies to increases related to Gardermoen Industrial Estate and the mobile heating central. This is, in the situation map in Figure 3.11, represented by the green lines. The energy production for the mobile heating central is expected to increase from the present level of 4,5 GWh, to about 35 GWh before 2022. The design load is hence expected to reach 15 MW in ten years.

In addition, it has also been planned to make a transmission line down to Jessheim, about 30 kilometers south of Gardermoen Industrial Estate. An increase in production from 0 GWh in 2013 to about 30 GWh in ten years is expected. For this extension, a new central is intended closer to Jessheim, to cover the demand in this area [11]. The load and production related to extensions for Jessheim will therefore not be evaluated in this report.

The purple curve shows the total expected energy demand and design load for the next ten years. The expected design load reaches 65 MW and the production close to 160 GWh.

Further evaluation will focus on:

- Extensions related to the heating central (red curve)
- Extensions related to the mobile heating central (blue curve)

By assuming the same production pattern as for the present centrals, the predicted duration curve for both centrals is presented in Figure 3.14 and Figure 3.15.

Within 2022, the heating central's proposed increase in load is 15 MW, while production increase will be 30 GWh. This gives a total design load of 37,4 MW, as can be seen in the figure below.

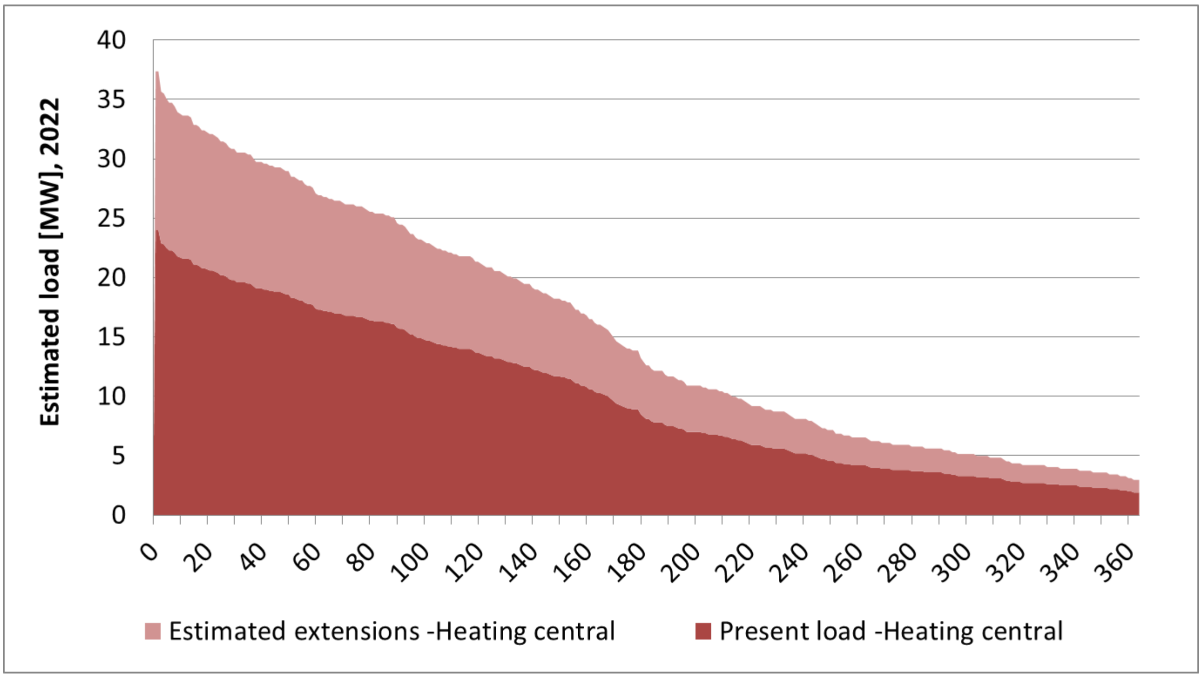


Figure 3.14 – Estimated duration curve for the heating central [MW]

As presented in chapter 3.1, the total capacity of the present heating central is 40,6 MW. This means that the present installations of the central can, in theory, cover the increase in demand. However, there are several factors that contribute to requirements for a higher capacity.

Flexibility in the choice of heat source can contribute to a higher economic profit. During the period from February to May 2011, electricity prices were high. In this period, the oil and bio-fuel burners were the only installations in operation. With lower capacity than at present, outsourcing the most costly alternative would not be possible, hence the profit would decrease.

In addition to flexibility, a relatively high capacity is necessary to provide redundancy, especially due to the airport's dependence on the heat source. With a low safety margin the consequences could be high if one boiler fails. Reliability of the system would decrease.

The relative expansion of the heating central will however not be as large as for the mobile heating central. Figure 3.15 shows a great need for a higher installed capacity in the mobile heating central.

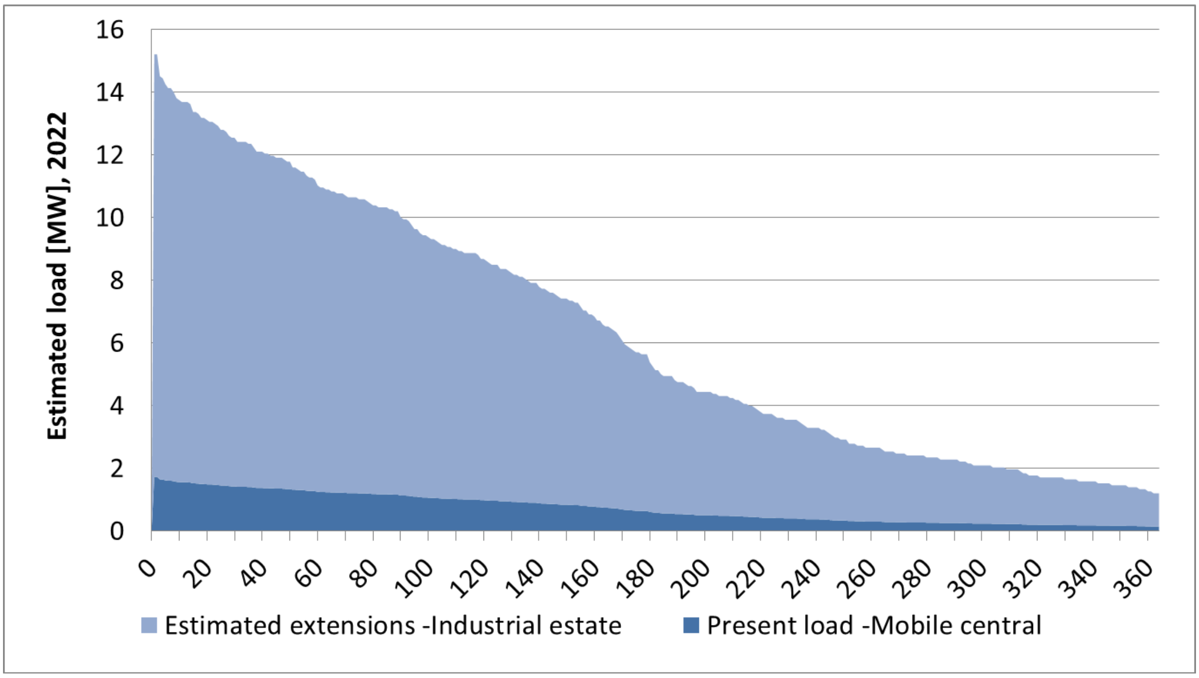


Figure 3.15 – Estimated duration curve for the mobile heating central [MW]

For both the heating centrals, the new *required* capacity will need to exceed the estimated peak load presented in Figure 3.14 and Figure 3.15, due to the redundancy and the cost effective aspects.

The total estimated load expansion (excluding expansions to Jessheim, Figure 3.12), emerges from Figure 3.16.

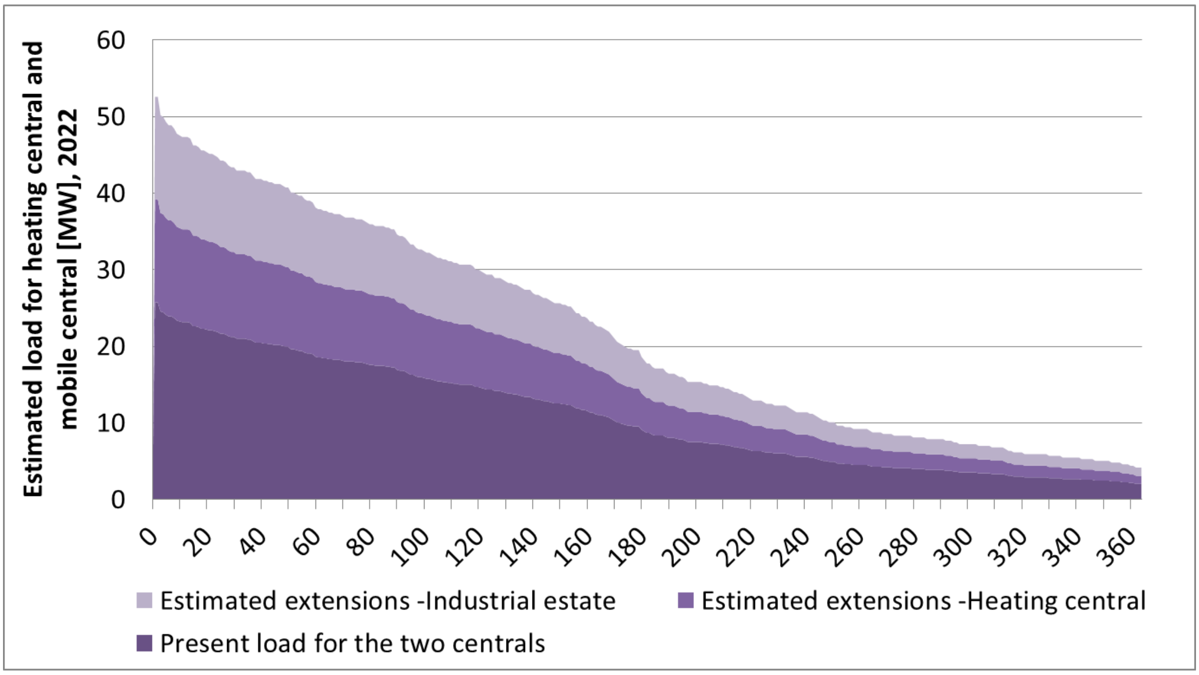


Figure 3.16 – Estimated duration curve for both centrals [MW]

Considering the system as a joint system, the extensions of the centrals lead to a doubling of the total design load, where the relative increase for the mobile heating central is the most extensive.

In the next section evaluations are made to determine whether the grid is designed for these extensions.

3.3 Evaluation of the extended centrals

The grid and its dimensions are of particular interest when evaluating the possibility of extension.

An upgrade of the pipe dimensions of the existing grid is considered a complex task. It is therefore important to determine whether a higher design load and thus mass flow (given that the original water temperatures remain the same) will cause excessive pressure drop in the distribution pipeline, exceeding recommended limits.

Temperature in/out of heating central at present

The proper selection of feed and return temperature for the entire system is of great importance to secure energy and cost efficiency in district heating. These determine the necessary amount of water circulated and the dimensions of the pipes. The heating central has been dimensioned with a feed temperature of approximately 110^{o}C for dimensioning winter conditions, while the summer conditions are dimensioning for the hot tap water. Figure 3.17 presents the heating central's measured feed and return temperature from February 2011 to January 2012.

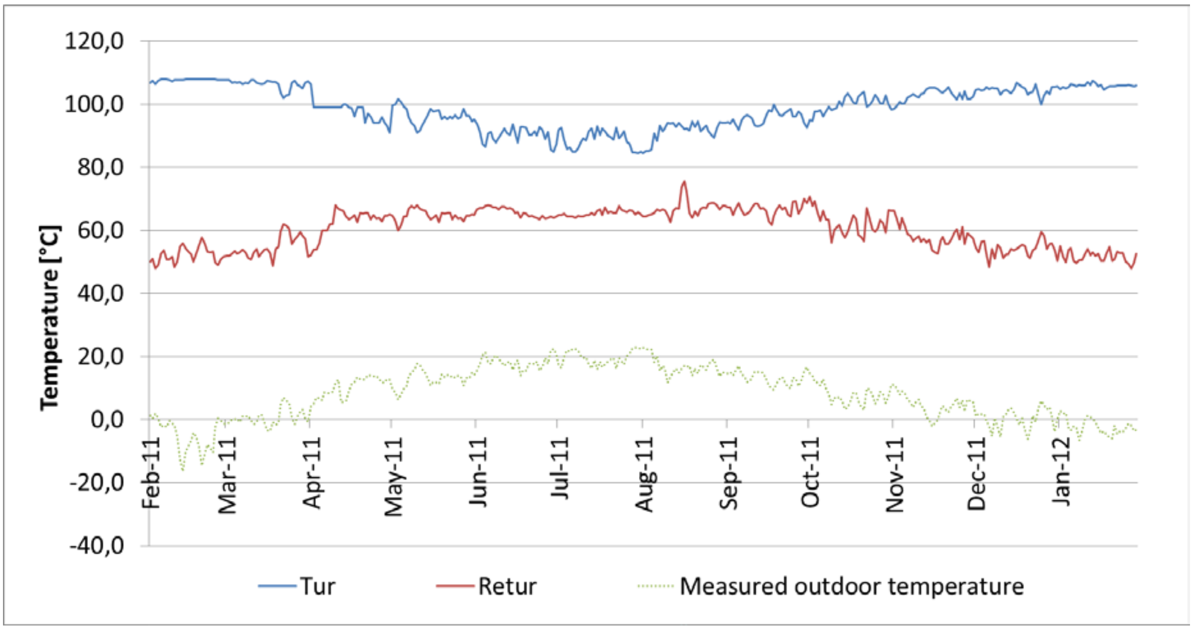


Figure 3.17 – Measured feed and return temperature

No temperature measurements have been available for the mobile heating central. However, Hafslund's operator at Gardermoen has specified that the feed temperature of the mobile heating central will be slightly lower than for the heating central [13].

The local installations at the customer (radiators etc.) are dimensioned for a specified range of feed and return temperatures. Increased heat demand could either be solved by increasing water volume and/or increase the difference between feed and return water temperature, *ΔT*.

Required mass flow and temperature interval of the heating central

The mass flow out of the heating central is dependent on the load required, and is between 50 and 350 m^3/h (14 and 97 kg/s) [11]. The recommended maximum velocity in the pipes is 2 m/s [1].

With the initial Δ*T* of the system at maximum (60 K), see January and February in Figure 3.17, the mass flow reaches the present maximum value of 97 kg/s to deliver the required load of 24 MW. This gives a velocity in the 250mm pipes exiting the central of 1,98 m/s, which is close to the recommended maximum.

As the district heating network connected to Hafslund's heating central is to be extended to cover a higher heating demand, a limitation to the performance and the capacity of the facility may be the design criteria the pipe system has been built for.

An enlargement in the delivered heat presupposes that the capacity must be increased, either by upgrade of the pipe dimensions or facilitate for a higher Δ*T*.

Increasing solely the mass flow to cover the increased production, would lead to a mass flow of 148 kg/s, and a velocity in the pipes of approximately 3 m/s.

As an alternate solution, Δ*T* of the system can be increased to keep the velocity within the recommended limits. However, as the increased production is high, and return temperature is already at 50ºC during the coldest periods in winter, solely increasing Δ*T* would mean that return temperature is just above 20ºC (with feed temperature at 110ºC), which is not feasible.

A combination of the two solutions may be achieved. It is however not unavoidable that a an upgrade of the grid must be done, as maximum mass flow for the 250 mm pipe is 98 kg/s to keep within recommended velocity limit. Which measures are chosen to cope with the increased production must be seen in an economic relation, which is not treated in this report.

For the mobile heating central, the expansion involves an increase from present installed capacity of 3,4 MW to 15,2 MW. The pipes (inner diameter of 250mm from this central also) are in this regard sufficient to cope with the new expected load.

3.4 Discussion

The present plant consists of two centrals. The heating central is the main provider of heat to Oslo Airport Gardermoen and the area west of the runway, while the mobile heating central delivers heat to the industrial estate, situated south-east of the airport area. By looking at the joint system, of both the heating central and the mobile heating central, a load duration curve has been derived, based on Hafslund's registered load from February 2011, throughout January 2012. A design load of 25,7 MW has been found. A total production of 62,5 MW is represented as the area below the mean duration curve for the joint system. As the measured outdoor temperature for the evaluated year of production exceed the monthly average temperature, the production of 62,5 MW will be somewhat lower than for a normal year. A correction for heating degree days gave a corrected energy production of 74 GWh for the joint system.

The planned extensions related to the Oslo Airport Gardermoen area and the area described as the industrial estate, have been evaluated. By assuming that the extended load and production will follow the same pattern as for the present system, two load duration curves have been presented for the heating central and the mobile heating central, respectively. By 2022, the extended design load for the heating central has been estimated to reach 37,4 MW. For the mobile central, the new design load that has been derived from the load duration curve reaches 15,2 MW. It is considered necessary due to redundancy and cost effectiveness that the installed capacity for the two centrals is higher than design load. Especially for the heating central, which provide heat to Oslo Airport Gardermoen, redundancy in the system is necessary to ensure reliability of heat provision.

Due to restricted information gathered for the district heating grid (considered as sensitive information by Hafslund), evaluations of whether the planned expansion is feasible with today's pipeline dimensions have been limited. Considering the heating central, evaluations of ΔT at maximum and the current design load of 24 MW, gives an estimated velocity of 1,98 m/s in the 250mm pipes exiting the central. This is close to the recommended maximum. As the extension projected for the heating central by 2022 leads to a design load of 37,4 MW, this will lead to the velocity exceeding the recommended values if mass flow is increased keeping ΔT constant. A more detailed description of the grid and local installations is needed for further analysis.

For the mobile heating central, the grid capacity is relatively high, which means that the extended design load of 15,2 MW will lead to a maximum velocity in the pipes exiting the central within the recommended limit.

An implementation of the geothermal installation is suggested to be done in the mobile heating central. This is due to the heating central having a current installation (40,6 MW) covering the extension which is approximated to lead to a design load of 37,4 MW, indicating that new installations in this central is not absolutely necessary (neglecting redundancy aspects). The base load is covered by biofuel at present, and it is therefore not considered necessary, from an environmental perspective, to replace the biofuel boilers with geothermal energy. Replacing the biofuel boilers with geothermal energy is also considered to come at a very high and unnecessary cost. The enlargement of the heating central can be limited to include minor installations providing a higher redundancy and flexibility of the central, such as an extra electrical boiler or oil boiler.

The feed temperature of the mobile central is also stated to be lower than for the heating central, which is favorable for the geothermal installation, as the recoverable temperature from the geothermal wells is limited.

The mobile heating central is evaluated to be the most favorable central for a geothermal installation based on the findings:

- The mobile heating central has the highest relative increase of capacity (by 2022)
- The mobile heating central has a lower feed temperature
- The grid connected to the mobile central can cope with the estimated load and production extension

4 Geothermal Design

In this chapter evaluations for a geothermal design and implementation will be conducted. The estimated design load that emerges from Figure 3.15 will form the basis for the dimensioning of the geothermal system.

The heat engineering aspects of a geothermal installation is presented. Following this is a presentation of the input and output parameters of the calculation program that has been used.

Also, a suggestion for the top site installations including heat exchanger and circulation pump is presented. Finally, a 10 MW solution is suggested, which will cover the base load for the extended mobile heating central.

4.1 Heat Engineering

The estimation of technical parameters and variables in this report are based on a calculation program. In the following parts of the report this program will be referred to as “Geocalc”. Geocalc is a spreadsheet developed at the Department of Energy and Process Engineering at NTNU, and is designed for geothermal plants with two drilled vertical wells and a drilled sub-surface heat exchanger.

In this section the theoretical foundation based on thermal engineering will be presented. By introducing these aspects, computation of the development of both temperature profile along the walls of the well, and heat transfer coefficient over time can be found. The predicted outlet temperature from the production well and hence the delivered load can be found.

4.1.1 Foundation of “Geocalc”

From heat transfer theory for a hollow cylinder in an infinite medium, a temperature profile and heat transfer coefficient over time can be determined. The symbols that are used for determining the temperature profile are presented in Figure 4.1.

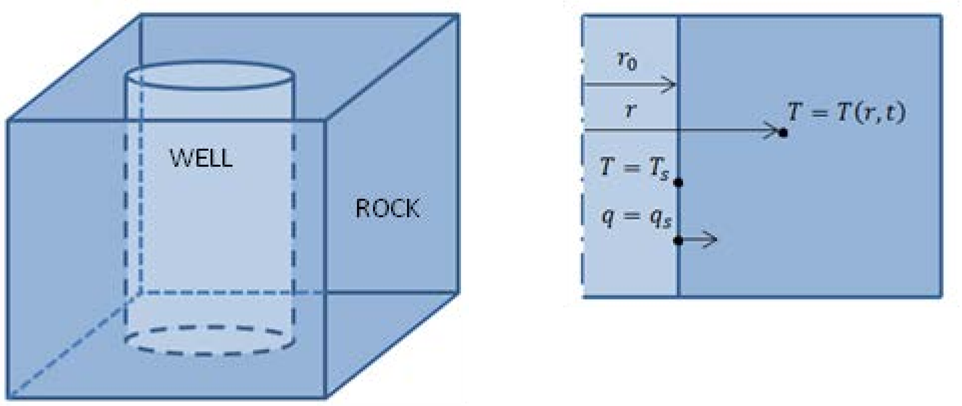


Figure 4.1 – Visualization of symbols used for heat transfer theory of a cylinder

By using cylinder coordinates the temperature profile around a cylindrical hole can be found as a function of time. The partial differential equation for conductive heat transfer in the rock is given by the following expression:

$$\frac{\partial^2}{\partial r^2}T(r,t)+\frac{1}{r}\frac{\partial}{\partial r}T(r,t)-\frac{1}{\alpha}\frac{\partial}{\partial t}T(r,t)=0 \tag{4.1}$$

The thermal diffusivity α is given by the thermal conductivity *k*, the density ρ and heat capacity c_p;

$$\alpha=\frac{k}{\rho c_p} \tag{4.2}$$

To solve the differential equation above, assumptions for constant surface temperature T_s in the borehole at a given depth are made. T_s will have approximately the same temperature as the flowing fluid at a given depth. There will however be some temperature changes in the first phase of the extraction. The water temperature, and hence the surface temperature T_s change relatively rapid the first days of operation, before the temperatures stabilizes. As the equation above assumes constant surface temperature in the borehole, better results can be obtained with as constant operation conditions as possible. This means that Geocalc is designed for cases where the mass flow is at steady state from starting phase and throughout the operating phase.

For constant surface temperatures the following boundary conditions can be used:

$$T=T(r,t)|_{t>0,r\geq r_0}$$

$$T=T_0|_{t=o}$$

$$T=T_s|_{t>o,r=r_0}$$

From these the following expression for the temperature profile at constant surface temperature can be derived [14].

$$T(r,t)=T_s+(T_0-T_s)\frac{2}{\pi}\int_0^\infty exp\left(\frac{-\alpha t u^2}{r_0^2}\right)\frac{Y_0(ur/r_0)J_0(u)-J_0(ur/r_0)Y_0(u)}{J_0^2(u)+Y_0^2(u)}\frac{du}{u} \tag{4.3}$$

where *u* represents an integration variable, and Y_0 and J_0 are Bessel functions of first and second order.

The heat transfer coefficient from the surface to the surroundings is defined as [15]:

$$h_s = \frac{q_s}{(T_s - T_0)} \tag{4.4}$$

where:

$$q_s = -k \left.\frac{dT}{dr}\right|_{r=r_0} \tag{4.5}$$

The heat transfer coefficient can now be calculated as follows [15]:

$$h_s(t) = \frac{4k}{r_o \pi^2} \int_0^\infty \frac{\exp(-\alpha t u^2)}{J_0^2(r_0 u) + Y_0^2(r_0 u)} \frac{du}{u} \tag{4.6}$$

Based on equation 4.3 for constant surface temperature a temperature profile can be visualized graphically as a function of time. This is illustrated in Figure 4.2. In this example T_s=90°C, T_0=150°C, c_p=860J/kgK, ρ=2600kg/m^3, k=3W/mK, d=0.2m.

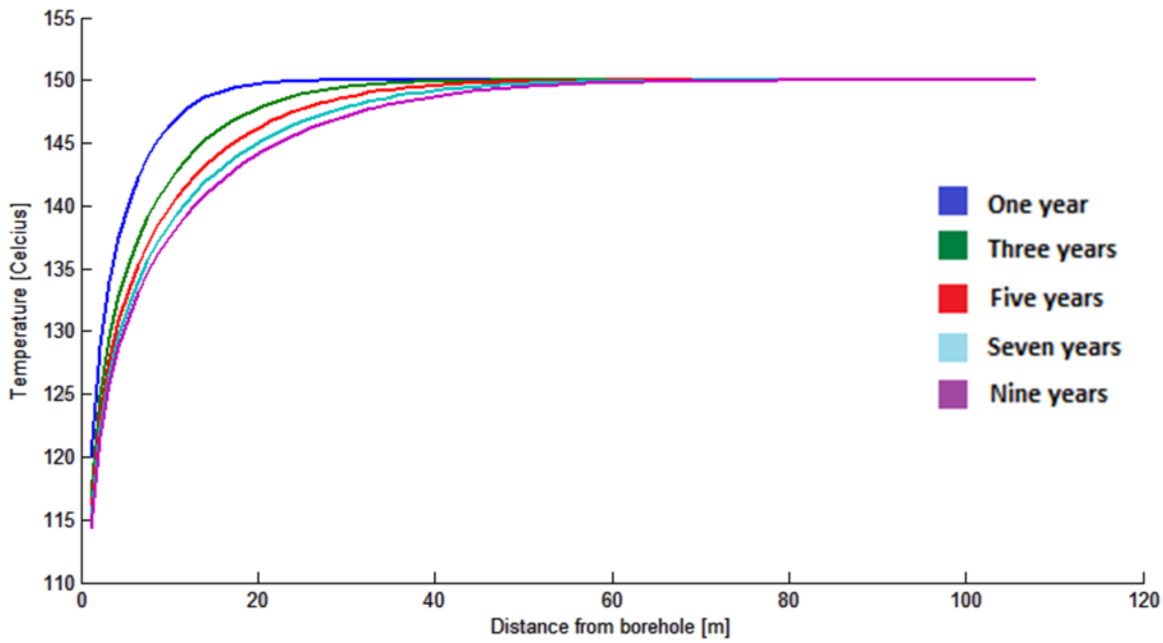


Figure 4.2 - Plot of temperature profile as a function of distance from borehole

Figure 4.2 shows the temperature profile as a function of the distance from wall at the entrance to the cross wells. The temperature span has a dispersion of 20 meter after one year, 35 meter after three years and 60 meter after nine years.

The heat transfer of the water flowing in the well is described by the following differential equation:

$$\dot{m}c_p \frac{dT}{dx} = \pi dh(T_s - T) \tag{4.7}$$

By solving for a pipe length *L*, we get the following solution [15]:

$$T_{out} = T_{0,out} - \frac{A}{C} + \left(T_{in} + T_{0,in} + \frac{A}{C}\right) e^{-CL} \tag{4.8}$$

where *A* is the temperature gradient along the borehole of unaffected rock [15]. *A* needs to be calculated from the vertical temperature gradient and the angle between borehole and horizontal plane.

$$C = \frac{\pi dh}{\dot{m}c_p} \tag{4.9}$$

The heat transfer over length *L* can now be found by:

$$Q = \dot{m}c_p(T_{out} - T_{in}) \tag{4.10}$$

Pressure loss will occur due to friction in the wellbores of the geothermal system. The pressure drop can be found from fluid mechanics [16];

$$\Delta p = \frac{1}{2} f \rho u^2 \frac{L}{d} \tag{4.11}$$

From [16] the friction factor can be estimated from the empirical correlation:

$$\frac{1}{f^{0,5}} = -1{,}8 log\left[\frac{6{,}9}{Re_D} + \left(\frac{k/d}{3{,}7}\right)^{1{,}1}\right] \tag{4.12}$$

where *k* describes the absolute roughness of the wall.

The Reynolds number is given by the following expression [17]:

$$Re_D = \frac{\rho u d}{\mu} \quad (4.13)$$

Due to the lack of test wells deeper than 1000m in Norway (1600m at The National Hospital [18]), no certain values for the parameters studied in this chapter can be obtained. The parameters can only be assumed to be within a certain range, based on geological knowledge. In the project thesis analytical solutions were solved for the temperature profile with constant surface temperature, varying three important parameters for the properties of the rock, namely the conductivity, specific heat and density. To see how these parameters affect the temperature profile, the reader is referred the project report, "Geothermal Energy for District Heating" [19].

4.1.2 Input and Output Parameter in Geocalc

When dimensioning a geothermal plant there are both geological and technical aspects that need to be taken into consideration. The calculations in Geocalc require a certain number of input and output values.

The following input parameters are included in Geocalc:

- The temperature gradient of rock and sediment
- Thermal conductivity of rock and sediment
- Density of rock and sediments
- Heat capacity in rock and sediments
- Depth of sediment
- Mean surface temperature
- Depth of plant (outlet well)
- Number of inlet well
- Length of cross wells
- Number of cross wells
- Angle for cross wells
- Diameter of outlet well, inlet well, and cross wells
- Roughness of walls
- Inlet temperatures
- Mass flow
- Equivalent usage time
- Usage time since start-up
- Lifetime of plant

- Dynamic or integrated values of heat transfer coefficient
- Efficiency of pump

The following output parameters are included in Geocalc:

- Outlet temperature
- Geothermal heat (kW)
- Total well drilling length
- Mass flow of fluid
- Heat transfer coefficient of inlet well, outlet well, cross wells for both rock and sediment
- Total pressure loss
- Pressure loss of inlet well, outlet well and cross wells
- Power loss of pump
- Power loss in % of geothermal plant
- Power loss of pump corrected for efficiency
- Temperature curves for water and rock along the accumulated length
- Curves for heat transfer along the accumulated length

Input Parameters for Gardermoen

The input parameters in Table 4.1 show the plant's requested input parameters compiled in chapter 2.2.6 and 3.3 in the project report "Geothermal Energy for District Heating" [19]. The input parameters are divided into four categories; *geological aspect, requested parameters for the district heating plant, requested parameters for the geothermal result* and *values for geometry.*

Table 4.1 – Input parameters to "Geocalc"

Geological aspects	**Values**
Mean surface temperature	5 °C
Temperature gradient	25 °C/km
Conductivity of rock and sediment	3 W/mK
Density of rock and sediment	2600 kg/m3
Heat capacity of rock and sediment	840 J/kgK
Requested parameters for the district heating plant	**Values**
Delivery temperature	80 °C
Return temperature	55 °C
Maximum heat demand	10 MW
Mass flow district heating	95,2 kg/s
Requested parameters for the geothermal results	**Values**
Equivalent usage time	5000 h/years
Usage time since start-up	10 years
Mass flow, geothermal	95,2 kg/s
Pinch temperature heat exhanger	2 °C

The usage time since start-up is set to 10 years. This is due to the fact that after a certain time span the power output will not vary considerably. The mass flow rate of the geothermal fluid is set equal to the mass flow rate of the district heating system.

In addition to this data, specifications regarding the geometry of the system are needed. With conditions as expected for Gardermoen, with a temperature gradient of 25°C/km, the required minimum rock temperature can be reached at depths below 4500 to 5500 meter. Between these depths, the cross well design will decide if the needed load can be achieved. Parameters for the cross well design are; *length*, *diameter of each cross well*, *number of cross wells* and the *angle between cross wells and horizontal plane*. The total length of the system is greatly dependent on the total length of the cross wells. By having a deeper reservoir with higher rock temperatures, parameters as length and number of cross wells can be reduced. Due to the high design load requirements for the mobile heating central at Gardermoen the depth of outlet well is set to 5500 meter. However, there are great technical challenges involved with drilling at these depths, which will have an impact on the economic aspects. Research shows an exponential growth in costs as a function of depth. And depths of 5 000 meter has until now marked the limit of what is economically feasible [20].

The depth of inlet well is dependent on the angle between cross wells and the horizontal plane. This angle has been set to 40 degrees, which gives an inlet depth of 4126 meter. Number of cross wells has been set to 21. To achieve the given load of 10MW, each cross well needs to have a length of 2138 meter.

The geometry data for the case is summarized in Table 4.2.

Table 4.2 – Geometry data

Values for geomertry	Values
Depth of outlet well	5500 m
Diameter outer well	12,5 ''
Number of inlet well	1 pcs.
Diameter of inlet well	8,5 ''
Length cross wells	2138 m
Number of cross wells	21 pcs.
Angle for cross wells	40 °
Roughness well walls	0,002 m

4.2 Suggested solution

The suggested solution presented is designed to meet the operating specifications given for the extended mobile heating central presented in chapter 3.2. The solution, presented in Figure 4.3, shall hence deliver a load of 10MW, which will cover the base load demand of this central.

Geothermal plant at	10,0 MW		Operating between	57 82	°C			
GEOLOGY			**GEOMETRY**			**HEAT PUMP**		
Surface temperature:	5	°C	Depth outlet well:	5500	m	Type:	0	Geoth.+ peak load
Temp.gradient sediment:	25	°C/km	Diameter outlet well:	12,5	"	Ekvivalent usage time:		h/year
Depth of sediment:	300	m	Number of inlet wells	1	pcs.	Heat from condenser		kW
Conductivity sediment:	3	W/mK	Diameter inlet well:	12,5	"	Calculated COP:		
Heat capacity sediment:	840	J/kgK	Length cross wells:	2138	m	Neceassary temp. increase:		°C
Density sediment:	2600	kg/m³	Diameter cross wells:	8,5	"	Heat from compressor:		kW
Temp.gradient rock:	25	°C/km	Number of crosswells:	21	pcs.	**ECONOMICS**		
Conductivity rock:	3	W/mK	Angle for cross wells:	40	°	Heat transfer model:	2	Average
Heat capacity rock:	840	J/kgK	Roughness well walls:	0,002	m	Interest rate:		%
Density rock:	2600	kg/m³	Total well drilling length:	54524	m	Electricity cost:		ore/kWh
CIRCULATING PUMP			**GEOTHERMAL RESULTS**			Economic lifetime of plant:		år
Efficiency:	0,85		Ekvivalent usage time:	5000	h/year	Drilling cost model:	1	Preliminary model
Pressure drop:	7,0	bar	Usage time since start-up:	10,00	years	Drilling cost:		mill kr
Powerloss:	68,6	kW	Geothermal heat:	9990	kW	Investment heat exch.		mill. kr.
Powerloss % of geo. heat:	0,69	%	Inlet temperature:	57,0	°C	Drilling cost pr. meter:		kr/m
Electricity use:	80,7	kW	Outlet temperature:	81,97	°C	Operating cost geothermal:		mill kr/år
PEAK LOAD			Mass flow geothermal:	95,2	kg/s	Energy cost geothermal:		ore/kWh
Type:	3	El-boiler	Pinch temperature heat exch.:	2	°C	Investment heat pump:		mill kr
Ekvivalent usage time:	0,00	h/year	**DISTRICT HEATING**			Operating cost heat pump:		mill kr/år
Power from electrical boiler:	10	kW	Delivery temperature:	80	°C	Energy cost heat pump:		ore/kWh
Temp. from electrical boiler:	80,0	°C	Return temperature:	55	°C	Investment peak load boiler:		mill kr
Efficiency electrical boiler:	90	%	Maximum heat demand:	10000	kW	Energy cost peak load boiler:		ore/kWh
El. cost:	0	ore/kWh	Mass flow distr. heating:	95,2	kg/s	Energy cost complete plant:		ore/kWh

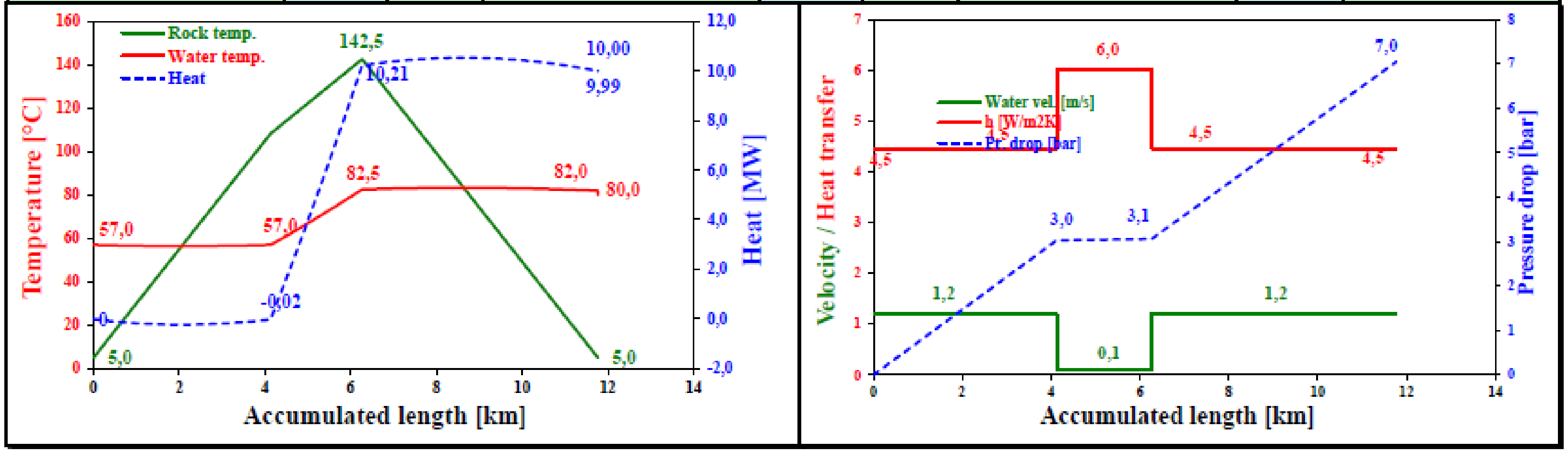


Figure 4.3 – Geothermal installation of 10 MW

Other dimensions and thermal output has been considered. This is presented in the project report, “Geothermal Energy for District Heating” [19]. It will for the following sections of this report be assumed a thermal output of 10 MW, with dimensions as presented above.

Discussion of Output Parameters

As Figure 4.3 shows, the total drilling length of the system, is 5452,4 km. The cross wells account for 82% of total length, while the outlet and inlet well account for 10% and 8%, respectively.

The geothermal result show an achieved load of 10 MW, an inlet temperature of 57°C and an outlet temperature of 81,97°C. With a pinch temperature of 2°C for the heat exchanger the delivery temperature for the district heating system will reach the required temperature of 80°C.

As can be seen in the temperature/accumulated length graph in Figure 4.3, the inlet water temperature will have a constant temperature of 57°C before it enters the cross wells. Through the cross wells the water temperature will increase by 25,5°C, giving a temperature of 82,5°C. A temperature reduction of 0,5°C will occur throughout the outlet well.

In the project report “Geothermal Energy for District Heating” [19], the preferred isolation thickness in the vertical wells of the geothermal system were evaluated. Due to the system’s total length of wells being large, insulation thickness will have impact on both the technical performance of the system and the resulting cost. Equation 4.11 describes how the pressure loss depends on the friction coefficient, velocity, density and diameter. As the insulating layer increases, the diameter of inlet and outlet well decreases. This will lead to a higher pressure loss. However, the need for insulation declines with an increase of mass flow. For the suggested solution in this report, a temperature reduction of 0,5°C throughout the outlet well is considered low, and the need for insulation is therefore not present. For a smaller system with a lower mass flow, insulation must be taken into consideration.

The pressure drop/accumulated length graph show how the pressure drop develops throughout the system. Pressure drop will mainly occur at the inlet and outlet well of the system, while it is low throughout the cross wells. The diameter of the cross wells is reduced compared to the inlet well, from 12,5” to 8,5”. Nevertheless, due to a high number of cross wells (21 pcs), velocity decreases from 1,2 m/s to 0,1 m/s. The pressure drop, which is a function of velocity squared, will hence abate. The blue curve shows a total pressure drop of 7 bar throughout the system, which will contribute to a total power loss of 68,6 kW.

4.2.1 Requirements to reinjection pump and heat exchangers

The two main top site elements that need to be taken into consideration are the reinjection pump for the geothermal fluid circulation, and the heat exchanger. Based on the geothermal solution presented, two suggestions for pump and heat exchanger are presented, based on two offers from Grundfos CAPS and GEA Heat Exchangers. The offers are attached in

Appendix B. In Chapter 5.7, both the pump from Grundfos and the heat exchanger from GEA Heat Exchangers will form the basis for material inventory in the life cycle assessment.

As emerge from Table 4.3, the heat exchanger must meet the following requirements for heat transfer.

Table 4.3 – Heat exchanger requirements

Geothermal side (water)	**Values**
Inlet temperature	57 °C
Outlet temperature	82 °C
Mass flow geothermal	95,2 kg/s
District heating side (water)	**Values**
Delivery temperature	80 °C
Return temperature	55 °C
Mass flow district heating	95,2 kg/s

The specifications give a log mean temperature difference (LMTD) of 2 K, while the Δ*T* for both sides of the heat exchanger is 25 K. The number of thermal units (NTU) is hence 12,5. The proposed heat exchanger is a GEA ECOFLEX Plate Heat Exchanger with 589 plates of stainless steel (AISI316) and a total heat transfer area of 704,4 m^2. The internal flow's specifics have three passes and 98 channels, which will result in a relatively high pressure drop of approximately 140 kPa.

To reduce the heat transfer area and the pressure drop (and the price), the temperature on the district heating side of the exchanger must be reduced. If one could allow a return temperature of 49°C and a delivery temperature of 79°C, the heat transfer area can be reduced to 290,7m^2, the number of plates to 287, and the number of passes to only one (143 channels). The pressure drop is reduced to 70 kPa. An offer with these specifics is also attached in Appendix B.

The reinjection pump must meet the requirements that emerge from Table 4.1, to pump the water through the geothermal system.

Table 4.4 – Pump requirements

Pump specifics	**Values**
Circulating medium	water
Mass flow geothermal	95,2 kg/s
Inlet temperature	57 °C
Outlet temperature	82 °C
Pressure loss	7 bar

The pump proposed is normal priming, single-stage centrifugal pump, used for pumping clean, non-reactive low viscosity fluids.

4.2.2 Geothermal installation at Gardermoen

Evaluations are based on the estimated increase in design load for the mobile heating central within the year of 2022, the temperature in and out of the centrals, and the evaluated capacity of the grid.

Implementation to the mobile heating central:

In chapter 3.2, extensions for both the heating central and the mobile heating central were presented. The duration curves in Figure 3.14 and Figure 3.15 showed how the relative increase in capacity was considerably higher for the mobile heating central.

Seeing that the mobile heating central must in any event be extended with new installations in the central to meet the extended load, whereas the heating central already has an installed capacity to meet the needs, it is proposed that Rock Energy's geothermal installation will be implemented in the mobile heating central to cover base load demand. The heating central will need new installations to meet the peak load demand, which presupposes a more flexible energy source, e.g. electrical boilers or oil fueled boilers, and in this case with the already installed bio fuel boilers this central will not be suited for a geothermal installation.

The geothermal installation at the mobile heating central will be able to cope with the base load of the system, and hence cover approximately 90% of the total energy demand. This is presented in Figure 4.4. The peak load will be covered by both the already installed boilers fired by bio fuel and electricity, and summarized this will give a capacity of 13,4 MW. The expected design load is estimated to reach approximately 15 MW, implying that new energy flexible installations must be installed in addition to the geothermal system.

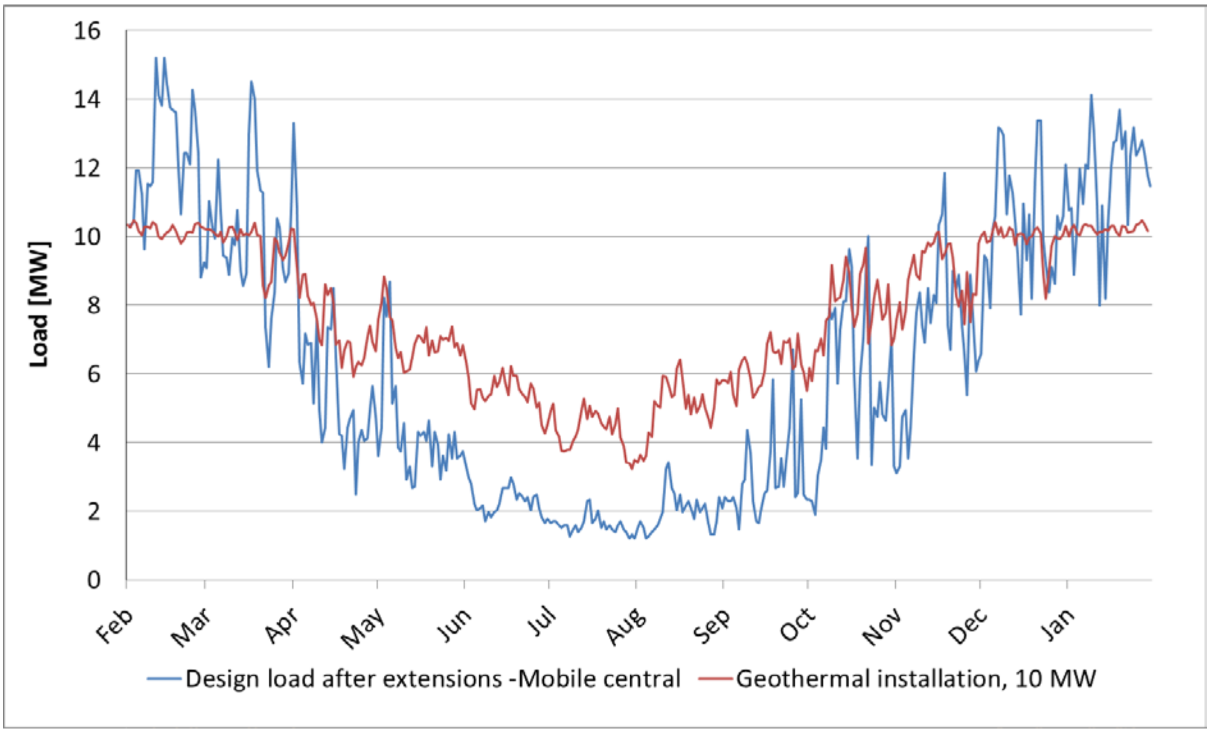


Figure 4.4 – Geothermal contribution for the mobile heating central

From the figure it is seen that with the geothermal capacity at 10 MW an over dimensioning occurs during the summer months when energy demand is low. It is nevertheless what would be the case in any installation where summer demand decreases with increasing temperature. A possible utilization of this energy is to meet the cooling demand in the area. However, no information of the potential cooling demand in the area is gathered for this report, and will thus not be relevant for the case studied.

A suggested geothermal implementation to the mobile heating central is presented in Figure 4.5.

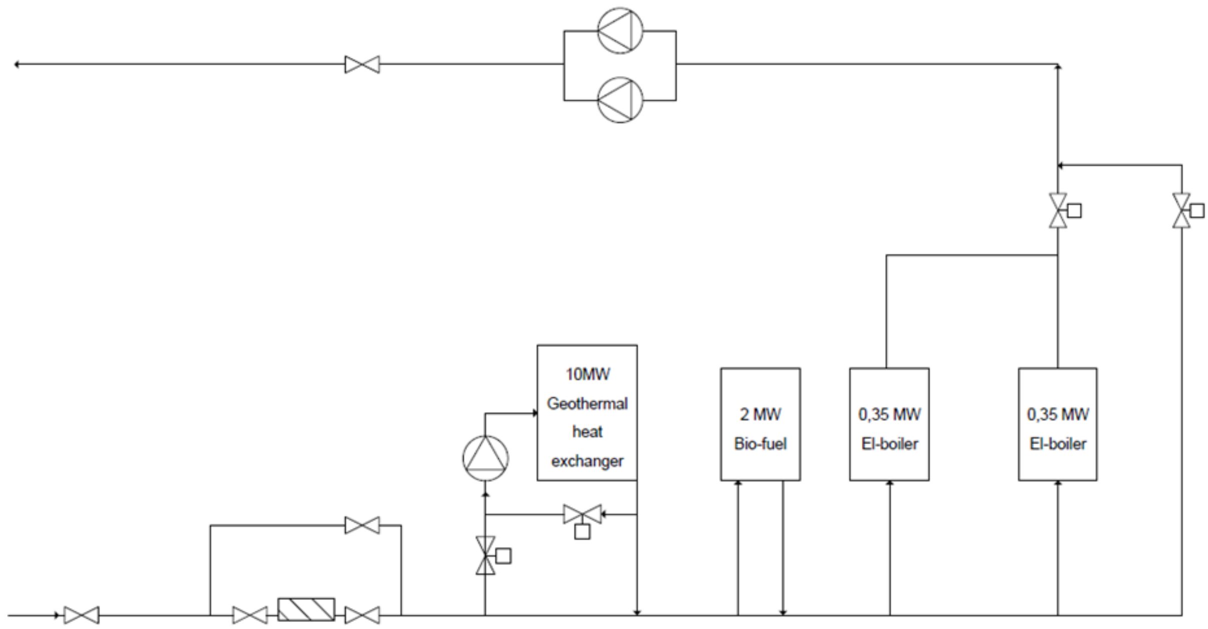


Figure 4.5 – Mobile heating central with implemented geothermal heat exchanger

The heat exchanger for the geothermal system will be connected in series to the other boilers in the mobile heating central. In this way the geothermal source will provide the first temperature lift of the cold water returning to the central. The maximum temperature reached is 80°C. The mobile heating central at present delivers a temperature somewhat lower that the heating central, approximately feed temperature of 95°C when bio fuel boilers are used and 85°C when electric boilers are used. Return temperature is in the range 50-60°C. This creates a benefit for the geothermal system.

As mentioned previously, new installations in addition to the geothermal heat exchanger are necessary to meet peak load demand. This can be covered by for example a new electrical boiler or a gas or oil fueled boiler, but the choice will not be covered in this report.

5 Life Cycle Assessment

Based on the results from Chapter 4.2, a life cycle assessment has been conducted. To examine the environmental consequences of the system it will be appropriate to use a quantitative and analytical method for environmental impact, thus LCA is considered a suitable choice. The method is appropriate to use in this context as it describes each process in adequate detail and also make possible an evaluation of each contributing process individually.

This chapter presents the limitations and assumptions related to carrying out an LCA for the system, as well as the findings and results of the analysis.

5.1 Objective

This report aims to evaluate the environmental consequences of a geothermal system based on Rock Energy's concept. At present, no system of this kind has been built, and thus an LCA on the system has not been conducted previously. The report aims at giving normative results for the environmental impacts. The method provides the ability to quantitatively compare the results to Enhanced Geothermal Systems, or other heat provision processes for district heating.

There are mainly two intended recipients that can take advantage of the LCA; Rock Energy AS who has developed the concept for the geothermal system discussed in this report, and the customer, Oslo Airport Gardermoen (with Hafslund operating the plant). An LCA will not only be applicable for the system at Gardermoen, but also other sites given that the site conditions are relatively similar. The results can be used in a comparative study of heat provision from different renewable energy sources, given that boundary conditions for the LCA's compared are equal.

5.2 Extent and Limitations

A significant portion of the work of this study is to evaluate what should be included in the system boundary, and at what level of detail the analysis should be implemented.

A geothermal district heating plant is considered a comprehensive system dependent on a large number of processes for every stage in its lifecycle. It is nevertheless believed to be the construction phase of the system having the largest impact on the environment, seeing that this phase has the largest number of contributing processes.

The life cycle assessment is in the report limited to include the construction of the well system, surface equipment directly dependent on the geothermal facility, operation and closure of wells. The thermal output of the system is 10 MW with 5000 annual operating hours, over a lifetime of 30 years.

Supporting equipment necessary for drilling, e.g. the drill rig, and the grid needed to transport the heat to the customers is not accounted for in this report. The latter is excluded due to it being installed already. The drilling rig is a complex product in itself, and is considered too extensive for the means of this analysis. It is also not known what share of the drilling rig's total lifetime the process of drilling the geothermal wells at the Gardermoen site will depend on.

It is important to emphasize that the analysis of this report will provide an overview of potential environmental effects, and not necessarily lead to the actual results of the system.

5.3 Functional unit

According to Chapter 2.3.2, the functional unit shall make sure that comparativeness in the LCA study is done on a general foundation and also reflect the goal of the study. The system dealt with in this report produces heat, usually measured in kWh. The collected data from today's heat production at Oslo Airport Gardermoen is given in kWh. It will therefore be appropriate to use the unit kWh to estimate the environmental impact of one unit produced. It is worth mentioning that it is common to use the functional unit MJ for heat providing processes, such as district heating. It has however been assessed that for this study it is appropriate to use kWh, due to comparisons to other geothermal LCA studies using the same functional unit.

5.4 Impact categories

Since greenhouse gas emissions is a current and appropriate topic for social development, it is particularly relevant to compare the different scenarios of this work on that basis. It is also highly relevant to compare greenhouse gas emissions of alternative energy sources to geothermal energy, as this can be decisive for development of environmental friendly energy production. Greenhouse gas emissions are covered in the impact category "global warming" and represented by g CO_2-equivalents/functional unit (which is kWh for the work of this report). All gas emissions contributing to global warming are converted into equivalents of CO_2. The global warming potential has a time horizon of 100 years, and its geographic scope is, as the name reflects, global scale [21].

At the same time, it is important to ensure that other considerations are taken care of, so that not a limited focus leads to unfortunate decisions.

Terrestrial acidification and freshwater eutrophication are both analyzed in this thesis, and these categories represent environmental impact of damages to ecosystems by toxic emissions, which in turn can cause loss of species. The terrestrial acidification impact category represents the increase in acidity and the potential impacts on ecosystems due to release of chemicals [22]. The time span of this category is eternity, and it is measured in SO_2-equivalents [21]. Freshwater eutrophication represents the potential impact on freshwater ecosystems due to release of chemicals (for example emission of ammonia) to air, water and soil [22]. Time span for this category is also eternity, and it is measured in P-equivalents.

Fossil depletion and metal depletion is also accounted for in this work. These categories are related to extraction of minerals and fossil fuels, and the categories have been established to concern protection of human welfare, human health and ecosystem health [21]. Its geographic scope is global scale. Fossil depletion and metal depletion is measured in oil-equivalents and Fe-equivalents, respectively.

An overview of the impact categories assessed in this report can be seen in Table 5.1.

Table 5.1 – Impact categories

Impact category	Unit/kWh
Climate change	kg CO2-Eq
Terrestrial acidification	kg SO2-Eq
Freshwater eutrophication	kg P-Eq
Fossil depletion	kg Oil-Eq
Metal depletion	kg Fe-Eq

5.5 Tools, databases

There are several tools, databases and methods for conducting an LCA. SimaPro is a simulation software developed to increase the efficiency of LCA studies, and it is connected to several databases. It is utilized by modeling the foreground system whereupon the software gathers the information for the background system related to the processes modeled. This software was intended to use for this work, but due to limited accessibility to the software a different method was chosen.

The work of this report is based on the Excel calculation tool ReCiPe, which is a method used for life cycle impact assessment. The method involves modeling of foreground system, and connecting it to the background system. Ecoinvent is a database utilized in the work of this report, and is meant for describing the processes of the background system. It has when possible been used data from Ecoinvent applicable to Norwegian conditions. In cases where processes for Norway have not been available, the data has been collected from the best match of similar processes.

5.6 Source Data

Conducting an LCA involves collection of great amounts of quantitative data. In this chapter a discussion concerning the choice and validity of data is presented.

5.6.1 Data collection

The data collection for this report's assessment comprises a combination of collected data from existing literature, the database Ecoinvent, published reports/articles together with a calculation model performed in Matlab. The input data for the calculation model is based on information collected from drilling experts and specialists within the relevant fields of study.

As far as it has been possible to verify the output data from the calculation with experts, this has been done.

5.6.2 Qualitative and quantitative information

A great portion of the information gathered for the life cycle inventory collection of this report is based on qualitative information, given by Rock Energy and experts on the field of drilling and geology. The information has to best efforts been transformed to quantitative data, as an LCA study is a systematic analysis which requires this to generalize the outcome for comparison and verifiability.

5.6.3 The validity of the information

The information gathered for the inventory of the study is, as discussed earlier, based on a collection of data from literature and own estimates conducted in cooperativeness with Rock Energy. The validity of the information gathered from Rock Energy will depend on whether the construction of the system will follow the present plan or not. If this is not feasible, e.g. if the time frame set for drilling, or other unexpected happenings occur, the input to the inventory must be revised.

The data collected from the literature should match the conditions for the system of this report to the best extent possible. For a geothermal system this will primarily be geological conditions at the site, the size of the facility and type of technology for energy conversion/distribution to the users. Because this is a completely new concept within geothermal energy extraction, the data are collected from geothermal projects in other countries than Norway, using EGS technology. It has nevertheless been validated that the data collected from EGS projects have the same type of geology as at the site this report is concerned with. This has mainly been a source for comparison, but in some cases the data has been used for the inventory collection in lack of other input data. Qualitative information has also been gathered from offshore drilling experts in Norway. It presupposes that the technical aspects of the drilling that will be conducted by Rock Energy are the same as for offshore drilling in Norway.

Obtaining information by personal communication has taken place at the arranged meetings with professionals in Trondheim and Oslo areas. As more questions arose later in the process, communication via email has been essential to obtain the necessary information.

The results have been validated as far as possible for this report. The environmental impacts of the system have been compared to environmental impacts of other geothermal systems. In this context some modifications are necessary to be able to compare the results, as the concept of Rock Energy’s sub-surface heat exchanger differs from traditional EGS concepts. Where comparison is done, the modifications are described.

5.6.4 Elements of uncertainty

The time limit of the work indicates that it is insufficient time to make extensive research in drilling technology and the data may therefore carry uncertainty partly because there has been made assumptions and approaches to complex systems.

The ideal approach to LCA is to collect or gain as much primary information as possible, and it has therefore been strived to do this for the work of this report. However, many uncertainties occur when drilling, and the exact outcome is hard to predict. The entry in the data collection that is considered to be most uncertain is the energy consumption for drilling. This entry is based on calculations with technical parameters discussed thoroughly with Rock Energy and experts in drilling technology. However, the results from the calculation differ greatly from the observed energy consumption for drilling at other sites with the same geological conditions. It has been evaluated as necessary to include an analysis using the observed energy consumption for drilling, due to the results' strongly dependence on this input parameter. The energy input to drilling is therefore assumed to be in the range between the calculated values and the observed values, and both endpoints in this range have been used in the analysis.

Another entry in the data collection considered to be uncertain is the water consumption for drilling. The water is used as drilling mud, and is injected into the drill pipe to transport the cuttings out of the well. The necessary mass flow rate of the drilling mud has been a source of discussion, and the energy used to pump the mud has been found to be greatly dependent on the flow rate. The interval of expected drilling mud flow rate is 2200l/min to 2500l/min. The endpoint 2500l/min was used in the analysis to secure that results were not underestimated.

Input data concerning material extraction and processing is gathered from the database Ecoinvent for this report. When data was not found for a particular process in Norway, it was replaced with the most representative process valid for Europe. An example of this is the steel used in casing. The input from Ecoinvent for this material is based on a mix of differently produced steels, which represents average world and European production mix. It is unknown what recycling rates and production mix are common for steel in Norway. These assumptions may therefore affect the results of this report.

5.6.5 System boundaries

The system boundary of an LCA is based on the purpose of the study, the intended application and audience, as described in Chapter 2.3.2. Also, data and cost constraints are relevant to consider when forming the system boundary.

One limitation of the LCA method is that is based on a model of system limits which often is a simplification of reality. This is also the case for this report. The drilling rig and the part of its total lifetime used for drilling the geothermal wells, the energy requirements for processing the drill heads, and drill site preparation, are all examples of processes that should be included in a more complete analysis. The material used for drill heads is nevertheless included in the analysis.

This work is limited to production of district heat to the grid. All other equipment in the grid is already installed at the site, and thereby left out of this report. The realization of the wells is particularly emphasized as it is expected to be the main contributor to environmental emissions. The processes involved in and the emissions from the construction of the well system have therefore been specially monitored.

A flow sheet for the system analyzed, with all the processes assumed to be most significant to the geothermal system, is presented in Chapter 5.7.1.

5.7 Life Cycle Inventory (LCI)

Inventory analysis involves data collection and calculation procedures to quantify relevant inputs and outputs of a production system [7]. In this section the foreground and background processes for Rock Energy's conceptual geothermal system will be presented. The results from Chapter 4, form the input criteria for the life cycle inventory. The size of the geothermal installation (10 MW) determines the depth of the wells and number of cross wells which will be applied when conducting the life cycle inventory collection.

Based on the flow sheet presented in chapter 5.7.1, quantitative data will be collected and presented. Information regarding the inventory calculation has been collected from mainly four sources:

1. Calculation based on technical data/parameters given by Rock Energy and drilling experts
2. Equipment specifications given by Rock Energy
3. Literature on LCA of geothermal energy extraction
4. Technical reports from geothermal drilling observations [23]

Where necessary, several sources have been considered to form the basis for input to LCA. Due to system differences, some parameters in the foreground system will only be valid for Rock Energy's conceptual system and thus a comparison to existing literature is not considered.

Quantitative data on basic processes in the background system such as extraction, processing of raw materials, energy supply and transport are collected from the database Ecoinvent.

A goal when performing an LCA is to collect as much primary information as possible about the system of interest. This will secure that the information is valid for the system at hand. In the case, no equal system has been built, and thus LCA data on this particular system is not obtainable. It is therefore especially important to gather enough primary data from Rock

Energy and drilling experts. One must also keep in mind that it is difficult to predict the outcome of drilling operations, as unanticipated events may occur. The data collected for this report has mainly been based on a “best case” scenario. It is taken into consideration incidents causing repair of mud motor and logging tools, which must be expected [24]. All other accidental or unanticipated events are not considered.

5.7.1 Foreground and background processes

It is convenient to distinguish between the foreground and background system. While the foreground system refers to the system of primary concern, the background system consists of generic data used to complete value chains upstream in the process. The background system, which is based on average data for different processes (such as transport, material extraction etc.), delivers energy and materials to the foreground system where more marginal data are required. A *flow sheet* makes it possible to distinguish between the foreground- and background system, and gives an overview of how the listed foreground processes interact with the background processes [9].

Figure 9.1, in Appendix C shows the flow sheet presented in the project report “Geothermal Energy for District Heating” [19], and the relation between the foreground and background system Based on Frick et al. [25].

The main contributing processes of a system based on Rock Energy’s concept are similar, but with some modifications. Particularly differentiating from an enhanced geothermal system (EGS) is the reservoir enhancement process. Whereas previously built geothermal systems have hydraulically fractured or natural reservoirs, Rock Energy plan to drill horizontal cross wells connecting the injection and production wells.

When conducting an LCA on Rock Energy’s conceptual geothermal system, it is convenient to distinguish between *construction-, operation-* and *demolition phase*. The processes related to the construction phase, can again be divided into two categories; *surface equipment* and *well system.* The flow sheet in Figure 5.1 presents the contributing processes of Rock Energy’s geothermal system.

The processes marked with grey represent the background processes, while the blue represent the foreground system.

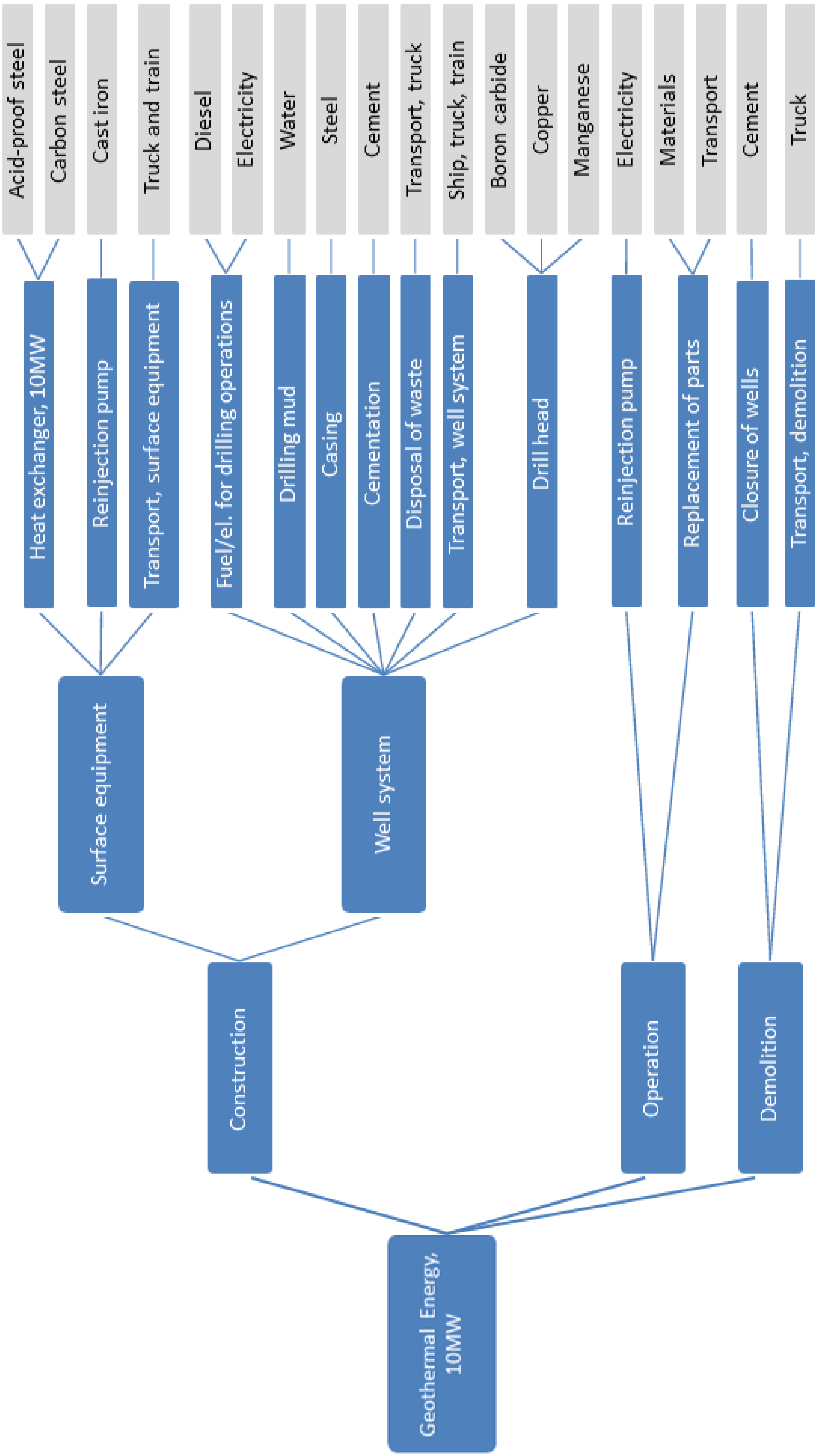


Figure 5.1 –Flow sheet for Rock Energy's patented geothermal system

5.7.2 Surface equipment

To determine the inventory of equipment needed at the top site of the geothermal wells, consultancy with Rock Energy has been determining. The inventory of the surface equipment takes into account that the district heating grid is already in place at the site, and is thus neglected for this analysis. Production and transportation can hence be neglected. The additional equipment concerning the connection of the geothermal system to the existing district heating installation has been accounted for in the life cycle assessment.

The inventory is developed by referring to the size of the plant (10 MW) and the results from "Geocalc" in Chapter 4.2, which determines the pressure loss in the circulation of the geothermal fluid which needs to be accounted for.

5.7.2.1 Heat Exchanger and reinjection pump

The proposed heat exchanger for the system, attached in Appendix B, is a GEA ECOFLEX Plate Heat Exchanger with 589 plates of stainless steel (AISI316). The amount of predominantly material for the heat exchanger, used in the plates and the casing, has been considered. The amount of each material needed for one heat exchanger has been collected from the Ecoinvent database. The overall life time of one heat exchanger is assumed to be 20 years. It has therefore been accounted for replacement of the heat exchanger or parts of the heat exchanger during the overall life time of the geothermal system.

The reinjection pump necessary to pump the geothermal fluid (also attached in Appendix B), and the amount of predominantly material is included. The overall life time of the pump is assumed to be 10 years.

Table 5.2 shows the assumed material input for the surface equipment. As there has been assumed a lifetime of 30 years for the geothermal system (50 years in the sensitivity analysis), this input is therefore adjusted by multiplying the material weight with a factor of 1,5 and 3 for the heat exchanger and pump, respectively.

Table 5.2 – Material inventory for heat exchanger and pump

Top site installation	Part	Material	Weight	Unit
Heat exchanger	Plate	Acid-proof steel	3800	kg
	Casing	Carbon steel	1500	kg
Pump	Pump casing Impeller	cast iron	1220	kg

5.7.2.2 Transport of surface equipment

The transport of surface equipment is difficult to determine as there are several links related to the delivery of the pump and heat exchanger. As the equipment as a whole is not recoverable in the Ecoinvent database (which would have included the transport of materials to the factory for processing and assembly), it has been included transport as if the materials came separately to the site. The transport of surface equipment to the site will therefore follow the same assumption as for construction of the well, described in Section 5.7.3.5.

5.7.3 Well system

As presented in the flow sheet in Figure 5.1 the contributing processes related to the completion of the wells and the cross well system can be divided into six partial processes;

1. Fuel/electricity consumption for drilling process
2. Mud for drilling process
3. Casing
4. Cementation
5. Disposal of drilling waste
6. Transportation associated with drilling process
7. Drill head material and handling

The data collection for each partial process is presented next.

5.7.3.1 Fuel Consumption for Drilling Operations

The fuel consumption for the drilling process of a geothermal energy installation is an important input parameter to the system being evaluated. The consumption of fuel is dependent on several factors such as depth of drilling, geological conditions at the site, quality of equipment being used, as well as time consumed when drilling. In the case of the geothermal installation at Oslo Airport Gardermoen, no equal system has been built previously and thus available data are not obtainable. It has therefore been constructed a model (Appendix D) to predict the fuel and electricity consumption of the drilling process for Rock Energy's concept of a sub-surface heat exchanger network.

The fuel consumption for drilling operations is in turn compared to other sources of data as described above.

Calculation model

Consultation with offshore drilling experts and geological experts set the frames for the model developed. There are mainly two contributing processes of an order of magnitude worth looking at for the drilling process. Firstly, the mechanical energy used for the lifting mechanism of the drill string and equipment in and out of the well and, secondly, the energy required for circulating the drilling mud so that the cuttings will be transported out of the well. The mud motor also contributes to rotation of the drill head. No hammering is necessary [26].

Several assumptions were taken when developing the model for calculating the energy contributions. These were made in cooperativeness with experts on the field.

It is assumed that the drill string must be lifted up from the well for every 385 meter. This is due to the drill head abrasion which leads to a replacement of the drill head for each 500 meter drilling interval. In addition, in approximately one out of four cases of which the drill head must be lifted up from the well, is due to other causes, such as repair of logging tools and mud motor [27]. Thereby an interval of 385 meter drilling before the entire drill string is lifted is established.

The drill string consists of several joints of drill string put together. Conventional drilling gear for offshore drilling is 9 meter drill string for each joint [27]. It is possible to lift three pieces of drill string (one stand) before one must disassemble or assemble the drill string. This means that for every 27 meters the total weight of which the rig must carry either increases or decreases, depending on whether the drill string is lowered or lifted. Each interval of lifting or lowering the drill (385 m) is therefore divided into 14 equal intervals of 27 meters each.

A maximum speed of 4 m/s has been assumed for lifting the drill [27]. It is furthermore assumed that this speed is reached within 4 seconds, giving an acceleration of 1 m/s^2, and that the distance of which the acceleration force is working is approximately 8 m. As mentioned, one stand of the drill string is lifted at a time, before the process is stopped for disassembly. Therefore the acceleration force is active multiple times for each lift to the surface. The crane performing the lifting of equipment is assumed to consist of two motors of 800 hp each [26, 28]. In reality, the load at which the motors deliver power will be variable depending on the depth (and hence weight) it is working at. Thus, at large depths the speed will not reach 4 m/s, and therefore this assumption is overly simplified. However, acceleration of the drill string can be assumed to have very little impact compared to the gravitational force, and is thus kept constant as explained.

When drilling takes place, the rig is holding the weight of the drill string and drill head minus the weight that needs to be applied down-hole. The weight on bit is set to be 20000 kg [26]. The effective drilling pace is assumed to be 7,5 m/h and 10 m/h for the 12 ¼''[2] and 8 ½'' drill heads, respectively [26].

The mass flow of the drilling mud is assumed to be 2500 l/min [29].

The parameters that form the basis for the calculation have been discussed with several experts on drilling, and are therefore based on their knowledge and experience.

The diameter of cross wells is set to 8,5'' and the diameter of the vertical wells is 12 ¼". This gives a thermal output of 10MW.

The main contributing input parameters to the calculation of mechanical energy consumption and the pump energy consumption is presented in Table 9.1 and Table 9.2 in Appendix E, together with reference source.

[2] Approximation from geocalc suggests 12 ½", but as drill bits are delivered at standardized sizes it is converted to 12 ¼" standard size

With these values, the calculation gives the theoretical values for energy consumption of the two processes as described in the Table 5.3.

In addition to the calculated energy requirements, Rock Energy has provided some information on the equipment intended for the drilling operation. The circulation of mud can be driven by a “12-P-160” Triplex mud pump [30]. The pump is driven by two 800 hp engines running at an average of 80% load during the drilling operation [24, 26]. With the assumed effective drilling speed of respectively 7,5m/s and 10m/s for the 12 ¼“ and 8 ½“ drill heads, and assuming operating hours for the pump being equal to the effective drilling time for both vertical and cross wells, the energy consumption becomes greater than the theoretically calculated values above.

Table 5.3 – Calculation of energy demand for drilling process

		Output	Value	Unit
Theoretical calculation	Mechanical energy (lifting)	Energy requirement vertical wells	25,2	MJ/m
		Energy requirement horizontal wells	30,9	MJ/m
	Hydraulic energy for pump	Energy requirement vertical wells	45,6	MJ/m
		Energy requirement horizontal wells	120,6	MJ/m
Equipment capacity	Hydraulic energy for pump	Energy requirement vertical wells	457,0	MJ/m
		Energy requirement horizontal wells	343,8	MJ/m

As the theoretical calculation differs greatly from the capacity calculation, it is clear that other contributions to energy demand in the theoretical calculation are present. This is discussed later in an assessment of the theoretical calculation compared to observations in drilling processes.

In agreement with Rock Energy the energy requirements for the LCA will be based on the equipment capacity for the pump, as well as the theoretical calculated value for mechanical energy, highlighted in the table above.

In following scenarios in chapter 5.9, where diesel is assumed to be the energy source for drilling operations, the efficiency is set to be 40%. Reported efficiencies of diesel engines are between 40 and 55% [31].

Literature - LCA studies related to geothermal energy utilization:

An overview of the sources and their respective source data for evaluation can be seen in Table 5.4. The level of detail in LCA studies on geothermal energy is in many cases modest. The geology at the sites, as well as diameter of well, is assumed to be important factors determining the energy consumption when drilling. It is unclear to what degree this is considered in the literature described in the table.

Table 5.4 – Diesel consumption based on litterature

Diesel consumption for drilling operation	Unit	Diameter of well [cm]	Depth of well [m]	Source
7,49	GJ/m	-	4800	Frick, 2010
7	GJ/m	20-40	5500	Bauer, 2008
9	GJ/m	15-70	<3000	Jungbluth, 2004
5	GJ/m	-	4500	Rogge, 2004
4,09	GJ/m	-	3010	Teuber et al., 1999

Technical reports covering geothermal drilling observations:

Data from the following technical reports summarize the reported amount of fuel consumed in drilling process for creating a geothermal well system. These reports are all confidential reports from the Soultz-sous-Forêts project on the border between France and Germany. Data is therefore recovered from a publishing having access to these reports [23].

1. GPK-3, Daily drilling report, 2002
2. GPK-4, Daily drilling report, 2004
3. GPK-3, Daily mud report, 2002
4. GPK-4, Daily mud report, 2004

Data concerning the fuel consumption are normalized by the length of the well, and multiplied by the specific heat of diesel. Values will hence be obtained in terms of "GJ/meter".

$$\frac{X\,[l]}{Y[m]} * 35{,}86 \left[\frac{MJ}{l}\right] = Z \left[\frac{MJ}{m}\right],$$ where 35,86 MJ/l is the energy density of diesel. (5.1)

For GPK-3, an amount of 500 000 liters (140 days for drilling) was obtained. Considering the specific heat of diesel the quantity of diesel consumed was 3.5 GJ/m [23].

For GPK-4, a much higher value was obtained (6.6 GJ/m). This is mainly due to the complications that arose during the drilling operations, which lead to an almost doubling of the drilling duration (230 days) [23].

Assessment of the theoretical calculation for the drilling operation compared to observations of diesel demand for drilling

Based on the results of the theoretical calculation (presented in Table 5.3 – Calculation of energy demand for drilling process) deviating greatly from the actual consumption of diesel for other similar drilling processes, it is suggested that there is too much uncertainty in such an operation to arrive at an exact theoretical value that can be used in an LCA analysis.

Possible causes of this deviation have been evaluated:

- Low efficiency of various basic components for drilling will generate large amounts of energy losses not accounted for in the theoretical calculation
- Friction loss will generate great losses
- The complexity of drilling makes it difficult to carry out the drilling at the maximum drilling speed at all times, thus approximately only 20-40% of the approved rate is utilized, giving an even lower efficiency [32]

It turns out that drilling speed and consumption are two variables that have low correlation when comparing experiences of different people who have been involved in such an operation [27, 29].

It appears in this situation that the most appropriate is to look at actual experience data on energy consumption of the drilling operations completed in similar environments, and compare these with the drilling operation Rock Energy will implement in their project at Gardermoen. This means that one should take into account factors that may affect the energy consumption of drilling:

- Bedrock
- Depth
- Diameter of well

Factors that are difficult to predict ahead of a drilling operation may also be of great importance:

- Time consumption for drilling
- Break-down of equipment
- Etc.

The conditions at the Soultz-sous-Forêts site concerning geology differ from what is found at Gardermoen. However, both sites are situated on a granitic basement. The sedimentary layer on top is larger for the Soultz site, approximately 1500 m and 150-200 m for Gardermoen [24]. Drilling in granite is considered a lot more time consuming and difficult and would imply that Rock Energy would have a disadvantage in this context. However, the equipment used at Soultz is somewhat “out-of-date” [28], and if possible, newer and more efficient equipment could give Rock Energy lower energy demand than that of Soultz.

Based on the literature review and calculations, it is decided to divide the energy input for drilling into the following two scenarios:

1. Energy input for drilling based on the measured values of diesel consumption at Soultz, 3,5GJ/meter.
2. Energy input for drilling based on calculated energy requirements based on information from Rock Energy and drilling experts (presented in the section “calculation model”)

Sensitivity of both of the scenarios has been tested for three energy sources; diesel and two mixtures of electricity (Norwegian and European conditions).

5.7.3.2 Mud for drilling operation

Information about the mud composition has mainly been discussed with Jan Evensen, Rock Energy and drilling experts [27, 29]. It has been agreed that it is possible to operate with pure water as drilling fluid. Components can be added to give higher viscosity to the mud, and thus provide more buoyancy for cuttings. It will on the other hand, when increasing viscosity, require more work to pump the drilling mud. It is difficult to calculate the trade-off between them. Pure water has been used in calculating the necessary pump work, it is therefore reasonable to stick to this option for further input to the LCA.

All drilling fluid is recycled (filtered with a shale shaker to remove cuttings) in a closed loop. It must however be replaced by fresh water from time to time.

The amount of water consumed is based on a mass flow of drilling mud of 2500l/min and ROP of respectively 10m/h and 7,5m/h for the 8 ½“and 12 ¼“ wells, with a recycling ratio of 80%.

Data from technical reports and literature

For comparison solely, data for the mud composition from existing literature was gathered from the report concerning the Soultz-sous-Forêts site [23].

The main elements used in the production of mud for GPK-3 and GPK-4 are; water, salt, caustic soda, bentonite, ecological lubricant and other chemical compounds (Mexel 432, Pac UL, tackle, etc). Note that the mud used for drilling in GPK-3 and GPK-4 consists essentially of water and salt, while often larger amounts of viscosity elements are used.

The mud composition concerning GPK-3 is shown in Table 5.5, together with data from Frick et al.

Table 5.5 – Drilling mud composition based on different sources

Composition of mud	Quantity - Technical reports (Soultz)	Quantity - Frick et al.	Unit
Water	1	0,67	m3
Salt	50	-	kg
Caustic soda	2,8	-	kg
Bentonite	5,8	7,7	kg
Chemicals	2,5	6,7	kg
Ecological lubricant	1,5	-	kg
Soda ash	0,6	6,7	kg
Starch	-	12,8	kg
Chalk	-	5,7	kg

5.7.3.3 Casing and cementing:

The sedimentary layer can be assumed to be 120-150 meters deep [24]. Casing is used from surface down to bedrock is reached to secure the sedimentary masses.

The estimation given by Rock Energy is casing of 9 5/8" extended down to 2 km, which is a conservative estimate.

The estimates from Rock Energy were given before the results of the geothermal installation were clarified (in Chapter 3). The diameter of the vertical section calculated in "Geocalc" resulted in a diameter of 12 ½" for the vertical wells. Due to this, the casing is upgraded to 16" casing (outer diameter). The dimensions of this casing are collected from standard API casing chart [33]:

- Outer diameter = 16"
- Inner diameter = 15.250"
- Wall thickness=0,75"

The total volume of 16" casing is thereby 23,752 m^3 for the 2 km, normalized per meter 0,0118759 m^3/m. The casing is made of steel, with approximate density of 8000 kg/m^3. Thus an amount of 95 kg/m is needed.

The amount of cement is approximated by a comparison to existing literature. See Table 5.6.

Table 5.6 – Cement based on different sources

Cement	Quantity [kg/m] - Lacirignola, 2011	Quantitiy [kg/m] - Frick et al.
Cement (Portland)	33,43	23,5
Cement (blast furnace)	4,9	7 (unspecified)

For the calculation of cement requirements in this report, an estimate of 30 kg/m of Portland cement has been used.

5.7.3.4 Disposal of drilling waste:

The amount of drilling wastes has been estimated by calculating the volume of the well and rock density. At Gardermoen the rock consists of mainly granite. The average density of granite is between 2,65 and 2,75 g/cm^3. 2,75 g/cm^3 is chosen as reference density. For the vertical wells (12 ¼") the amount of drilling waste is 0,218 t/m. For cross wells (8 ½") the amount of drilling waste is 0,101 t/m.

It is assumed that drilling waste will be transported to Oslo for use in road construction (e.g. Veidekke as a potential customer) [24], as crushed granite is in demand in large scale for road construction. The transportation is covered by truck, and the distance is approximated to be 50 km.

Transport is expressed as "tkm", the product of weight of the material and the transport distance, see Table 5.7.

Table 5.7

Drilling waste transportation	Quantity [tkm/m]
Vertical wells	10,9
Cross wells	5,05

Comparison to existing literature

The amount of drilling wastes was estimated by calculating the volume of the well and rock density (2.3 g/cm3 down to 1400 m, and an average of 2.65 g/cm3 for the other 3700 m are presented for conditions at the Soultz site [23].

Data collected show that drilling waste range from 0.29 t/m [23], to 0.456 t/m [25].

5.7.3.5 Transport associated with construction of the well

Considering the transport of materials to the drilling site, the following assumptions are made:

- Transport of 150km by truck for all elements
- Transport of additional 1200km by train for the steel components (casing), assuming an import from Eastern Europe

The assumption is made in cooperation with Thomas Gibon, co-supervisor in LCA.

5.7.3.6 Drill head material and handling

The drill bit sizes are determined to be 12 ¼" for the vertical wells and 8 ½" for the cross wells. The approximate mass of each drill head is 80 kg and 50 kg, respectively [27].

The drill heads' construction material consists of hard metal (carbide) with an addition of copper manganese. The copper manganese is infiltrated in carbide powder (tungsten carbide) at high temperatures. Typical composition of the components is 2/3 volume percent tungsten carbide and 1/3 volume percent copper manganese [27].

Based on information in Chapter 5.7.3, it is assumed that the drill heads must be replaced for every 500m drilling interval.

The life cycle of tungsten carbide is not recoverable in Ecoinvent database, and is thus replaced by the input of boron carbide, including materials, energy uses, infrastructure and emissions from processing of this material. Copper manganese (CuMn) is based on a composition of 86% Cu and 14% Mn, and is recovered separately from Ecoinvent.

The total demand of boron carbide is 2598,9 kg, and demand for CuMn 3431,1 kg, considering a 10MW geothermal system. See Table 9.3, Appendix E.

5.7.4 Operation

Once the geothermal system has been built and put to operation, minor contributions to the system are necessary. In the geothermal cycle the pressure drop need to be accounted for by the reinjection pump. This pump has been specified in Section 5.7.2, and it is driven by electricity input. The electricity use of 80,7 kW (see Figure 4.3), has been modeled in the inventory. The maintenance of the system is in this context limited to replacement of the pump and heat exchanger after the assumed lifetime of these components, as described in the section 575.7.2.

5.7.5 Closure of wells

The end of life of the plant is limited in this report to deal with the closure of the wells. The surface equipment is not considered in this context, but it may be reused if not damaged or worn-out.

The closure of the wells involves filling the holes with blocks of cement for safety reasons. The amount is considered in cooperativeness with Rock Energy. 350 meter of cementation in the 12 ¼“ vertical wells will form the inventory for the input to the closure of the wells, this is considered more than adequate for this purpose. Portland cement is implemented.

5.8 Summary LCI

A complete summary of the inventory described in the previous sections is presented in Table 5.8. Where appropriate, the values have been generalized to unit per meter well. This makes it convenient for application to other outputs of the geothermal system than 10 MW. Nevertheless, one must keep in mind that most values will be dependent on the diameter of borehole drilled, and the values may hence not be valid for other dimensions of boreholes.

The energy consumption for drilling is presented twice in the table, meaning that both scenarios of energy consumption will be considered further in this report. Due to the uncertainty of this input, in addition to the input being highly sensitive to the outcome of the environmental impacts of the system, it is considered necessary to consider both scenarios.

Table 5.8

Main contributing processes	Value	Unit	Comment
Diesel consumption - scenario 1	3,5	GJ/m	Based on Soultz reported energy demand
Diesel consumption - scenario 2	Vertical wells: 0,482 Cross wells: 0,375	GJ/m GJ/m	Based on theoretical calculated values
Electricity consumption - reinjection pump	12105000	kWh	30 years lifetime, output of 80,7kW
Drilling mud (water consumption)	7199	kg/m	
Cementation (Portland)	30	kg/m	
Steel, low-alloyed (material for casing)	95	kg/m	
Boron carbide (material for drill head)	0,0477	kg/m	
Copper Manganese (material for drill head)	0,0629	kg/m	
Acid-proof steel (material for heat exchanger)	3800	kg	Equivalent to one heat exchanger
Carbon steel (material for heat exchanger)	1500	kg	Equivalent to one heat exchanger
Cast iron (material for reinjection pump)	1220	kg	Equivalent to one pump
Disposal of drilling waste (transport)	Vertical wells: 0,482 Cross wells: 5,05	tkm/m tkm/m	
Transport of materials	All elements: 150 All steel components: 1200	km	Amount (tonnes) of materials is multiplied by distance to achieve the unit "tkm" in the input for LCA

5.9 Life Cycle Assessment (LCIA)

Simulations have been conducted for two main scenarios; one based on the input of energy for the drilling process being 3,5 GJ/m (corresponding to that of the Soultz-sous-Forêts project). The other scenario is based on the calculated energy demand resulting from input from Rock Energy, as described in Section 5.7.3. The energy demand for drilling is considered the largest contributor to environmental impact in the climate change category, but is yet the input of this report which is most associated with uncertainty. It is for that reason worth looking at these two scenarios. Both scenarios are conducted with constant input to the other categories in the LCI.

Rock Energy wish to utilize electricity at the grid (in Norway) for the drilling operation. In the first section of this chapter a comparison between the scenarios presented in Table 5.9 will be conducted.

Table 5.9 – Description of scenario 1 and scenario 2

Scenario	Assumed energy demand to drilling process	Energy supplier to drilling process	Thermal output	Lifetime
Scenario 1, electricity NO	3,5 GJ/meter	Electricity mix at norwegian grid	10 MW	30 years
Scenario 2, electricity NO	0,482 GJ/meter - vertical wells	Electricity mix at norwegian grid	10 MW	30 years
	0,375 GJ/meter - cross wells		10 MW	30 years

In addition to the Norwegian conditions, each scenario has been considered for alternative energy supply. This has been simulated with two other alternative energy sources. As Rock Energy has an ambition to become a leading geothermal company internationally, it is of interest to not only look at Norwegian conditions for electricity supply. Electricity at the grid in Europe has been simulated, as well as conventional energy supply of diesel.

The simulations are therefore divided into the scenarios presented in Table 5.10.

Table 5.10 – Two scenarios with different energy supplier for drilling process

Scenario	Assumed energy demand to drilling process	Energy supplier to drilling process	Thermal output	Lifetime
Scenario 1, electricity NO	3,5 GJ/meter	Electricity mix at norwegian grid	10 MW	30 years
Scenario 2, electricity NO	0,482 GJ/meter - vertical wells	Electricity mix at norwegian grid	10 MW	30 years
	0,375 GJ/meter - cross wells		10 MW	30 years
Scenario 1, diesel	3,5 GJ/meter	Diesel	10 MW	30 years
Scenario 2, diesel	0,482 GJ/meter - vertical wells	Diesel	10 MW	30 years
	0,375 GJ/meter - cross wells		10 MW	30 years
Scenario 1, electricity EU	3,5 GJ/meter	Electricity mix at european grid	10 MW	30 years
Scenario 2, electricity EU	0,482 GJ/meter - vertical wells	Electricity mix at european grid	10 MW	30 years
	0,375 GJ/meter - cross wells		10 MW	30 years

The electricity mix at Norwegian and European grid is presented in Table 5.11.

Table 5.11 – Electricity production sources for Norwegian and European electricity mix [18, 34]

Electricity mix	Geographic location	Electricity production source
Electricity, medium voltage, at grid, NO	Electricity production in Norway, import is included	Hydropower 70% Wind power 0,3% Thermal power 1 % Uknown origin 25% Import 3 %
Electricity, medium voltage, production UCTE, at grid	Electricity production in Middle and South Europe	Thermal nuclear 26,3% Fossil fuels 48,7% Hydraulic net generation 17,2% Other sources (wind, solar etc) 7,8%

Each scenario gives results for each of the impact categories: climate change, fossil depletion, freshwater eutrophication, metal depletion, and terrestrial acidification, described in Section 5.4. This chapter presents the results for each scenario together with a discussion of the outcome.

The purpose is to indicate which of the considered cases will give the lowest environmental impacts, and to identify relationships between processes in the system and environmental impact.

The results are compared to other literature to check the validity of the results, and to point out differences in environmental impact for different systems.

5.9.1 Comparison of scenario 1 and 2 – For Norwegian conditions

As described previously, the difference between scenario 1 and 2, is related to the energy consumption for the drilling process for the geothermal system. In this section a comparison of the two scenarios will be presented. As Rock Energy has specified that the drilling process is to be conducted be electricity, Norwegian electricity conditions are assumed.

The results in absolute values, for each impact category, are presented in Table 5.12.

Table 5.12 – Results of scenario 1 and 2

Impact category		Surface equipment	Well system	Operation	Closure of wells	Sum
climate change [gCO2-eq/kWh]	Scenario 2	2,337E-02	6,101E-01	2,932E-01	7,267E-02	9,993E-01
	Scenario 1	2,337E-02	1,713E+00	2,932E-01	7,267E-02	2,103E+00
fossil depletion [goil-eq/kWh]	Scenario 2	7,269E-03	1,735E-01	7,559E-02	7,053E-03	2,634E-01
	Scenario 1	7,269E-03	4,579E-01	7,559E-02	7,053E-03	5,478E-01
freshwater eutrophication [gP-eq/kWh]	Scenario 2	1,173E-05	3,433E-04	9,474E-05	2,918E-06	4,527E-04
	Scenario 1	1,173E-05	6,997E-04	9,474E-05	2,918E-06	8,091E-04
metal depletion [gFe-eq/kWh]	Scenario 2	3,251E-02	5,194E-01	3,461E-02	5,806E-04	5,871E-01
	Scenario 1	3,251E-02	6,496E-01	3,461E-02	5,806E-04	7,173E-01
terrestrial acidification [gSO2-eq/kWh]	Scenario 2	1,046E-04	2,362E-03	8,292E-04	1,168E-04	3,413E-03
	Scenario 1	1,046E-04	5,482E-03	8,292E-04	1,168E-04	6,532E-03

Figure 5.2 shows which of the system's processes are most contributing to each impact category assessed.

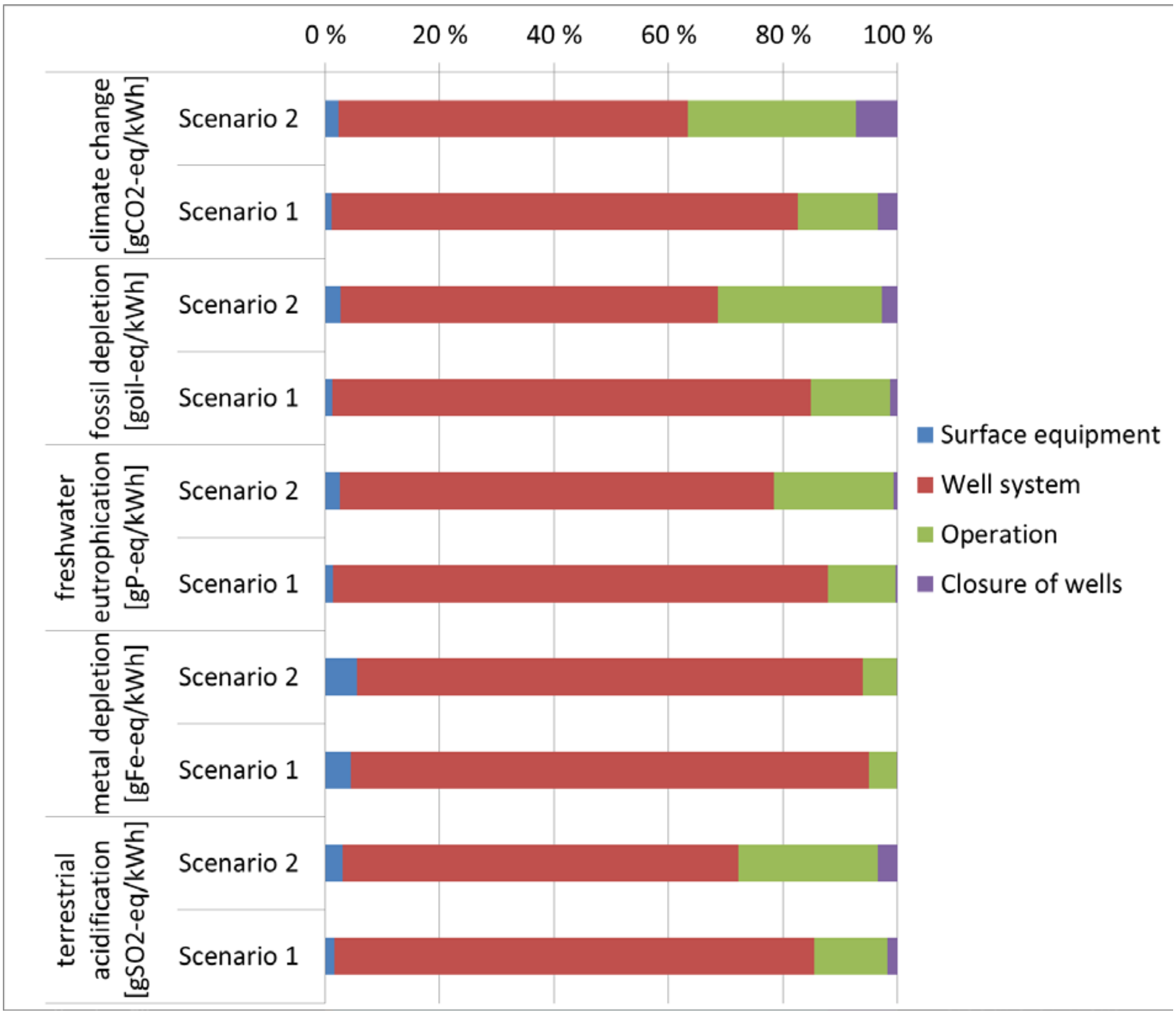


Figure 5.2 – Results of scenario 1 and 2

The relative contribution from the well system increases for all impact categories when increasing the electricity consumption (going from scenario 2 to scenario 1). The impact category metal depletion is the least sensitive category to these changes. This is due to this impact category's independency of electricity generation. As will be described later in this section, the most contributing processes related to metal depletion are the extraction and material production for the casing, heat exchanger and drill head. For the remaining impact categories, the trends are similar. The relative importance of the drilling process increases.

For the Norwegian electricity mix, the imported electricity (and from unknown origins), has the highest impact on the results. By looking at the results in Appendix F (Norwegian electricity mix, for scenario 1 and 2), one can see that the burning of hard coal and natural gas are the main contributing processes emitting greenhouse gases.

If the actual energy consumption for the system related to the drilling process turns out to be closer to scenario 2, the relative importance of the operation phase increases. By examining the opportunities of operating the facility by "green certificates," contribution from the operating phase can be reduced.

Climate change:

The main contributing processes related to the climate change of scenario 1 and scenario 2 can be seen in Figure 5.3.

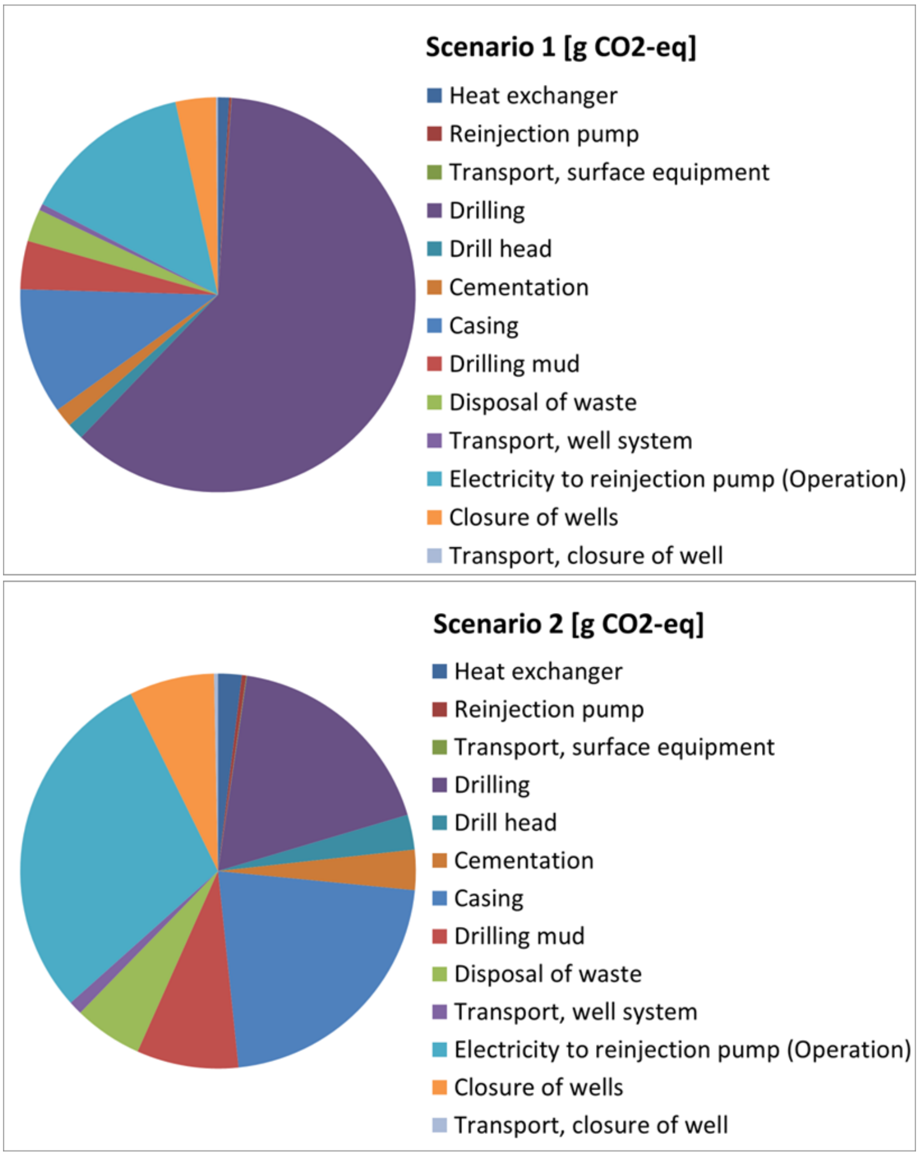


Figure 5.3 – Climate change results for scenario 1 and 2

For scenario 1, the drilling process contributes to more than 60% of the total emissions. For scenario 2, the drilling process is also a significant contributing process, but the processes related to casing and the pump operation (during a lifetime of 30 years) is of similar magnitude.

If scenario 1 and 2 is evaluated as worst and best case for a realistic geothermal system, the absolute value of the results for the climate change impact category will be in an interval between 0,9993 and 2,1026 g CO_2-eq/kWh (absolute value of scenario 2 and scenario 1, respectively).

Fossil depletion

The contributing processes for fossil depletion for the two scenarios can be seen in Figure 5.4.

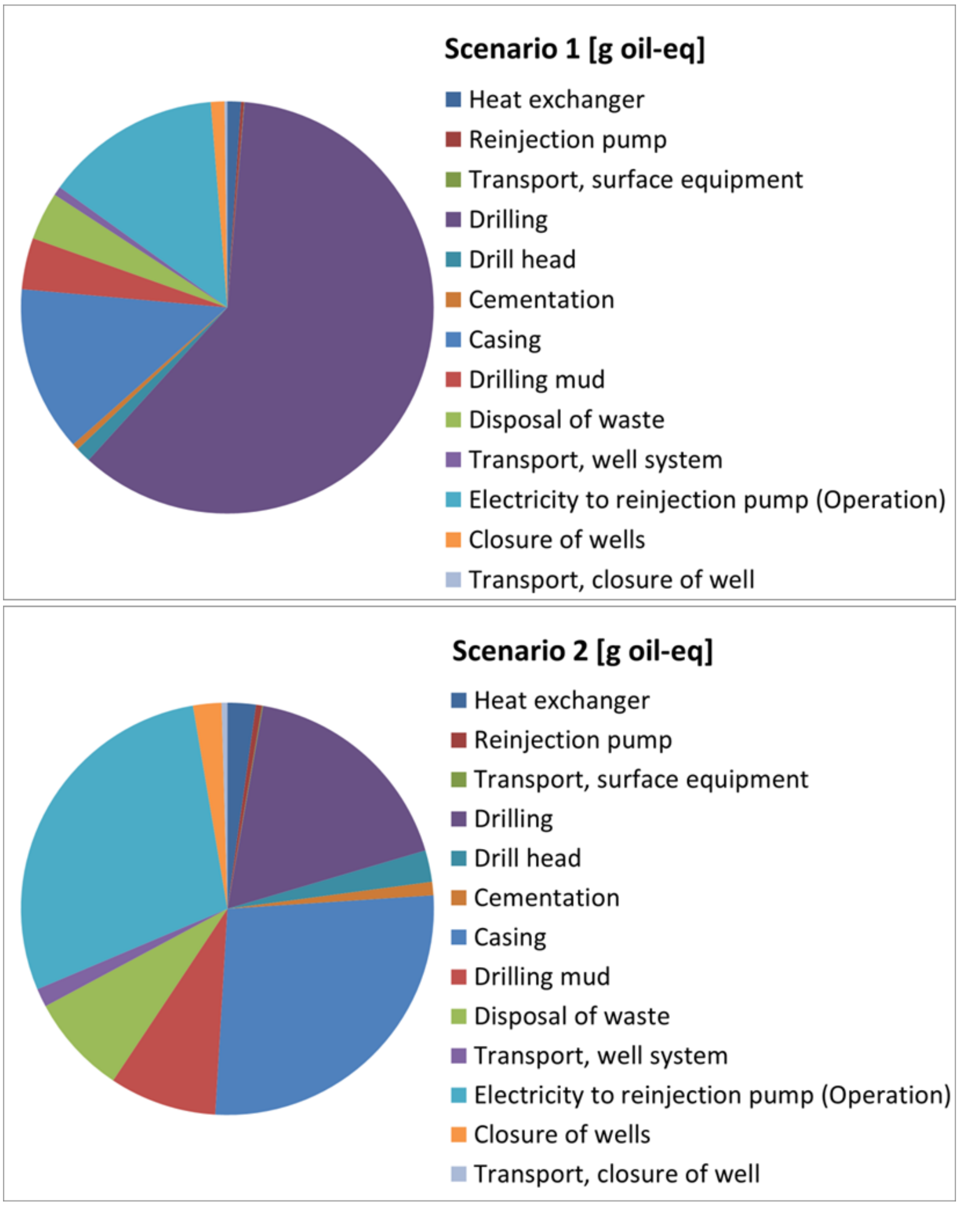
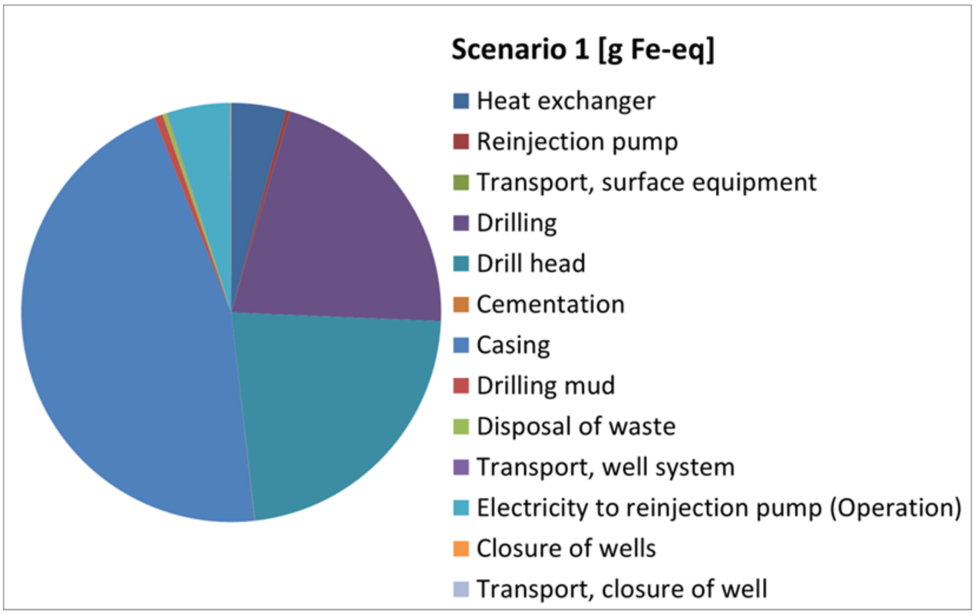


Figure 5.4 – Fossil depletion results for scenario 1 and 2

The results show the same tendency as for the climate change category. This can be explained by the correlation between the exhaustion of oil and fossil fuel, and the greenhouse gas emissions related to the combustion of it. The absolute value of the impact category, fossil depletion, is from the results expected to be in the interval of 0,2634 and 0,5478 g oil-equivalents/kWh.

Metal depletion

The results of the partial processes' contribution to the metal depletion are presented in Figure 5.5.



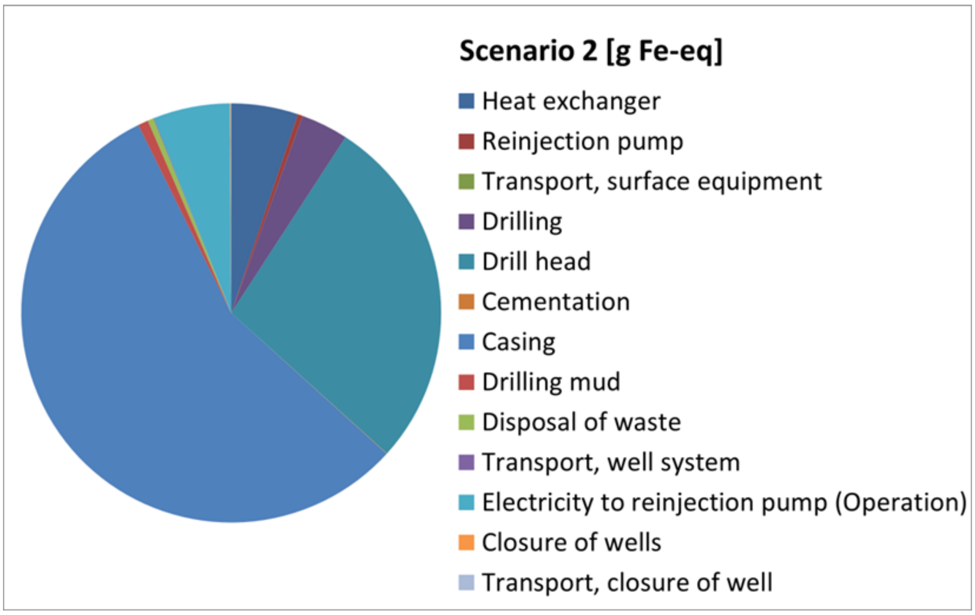


Figure 5.5 – Metal depletion results for scenario 1 and 2

For all of the processes involving extraction of metal in the geothermal system, the amount of metal used is held constant. Surprisingly the results show that the amount of consumed iron equivalents related to scenario 2 is higher than for scenario 1, with absolute values of 0,7173 and 0,5871 g Fe-eq/kWh, respectively. For scenario 1, the drilling process is more contributing than for scenario 1. This can be explained by the infrastructure related to electricity transmission, whereas conductors and masts require large amounts of metals, in particular steel, aluminum, and copper.

Freshwater eutrophication

Contributing processes to the freshwater eutrophication can be seen in Figure 5.6.

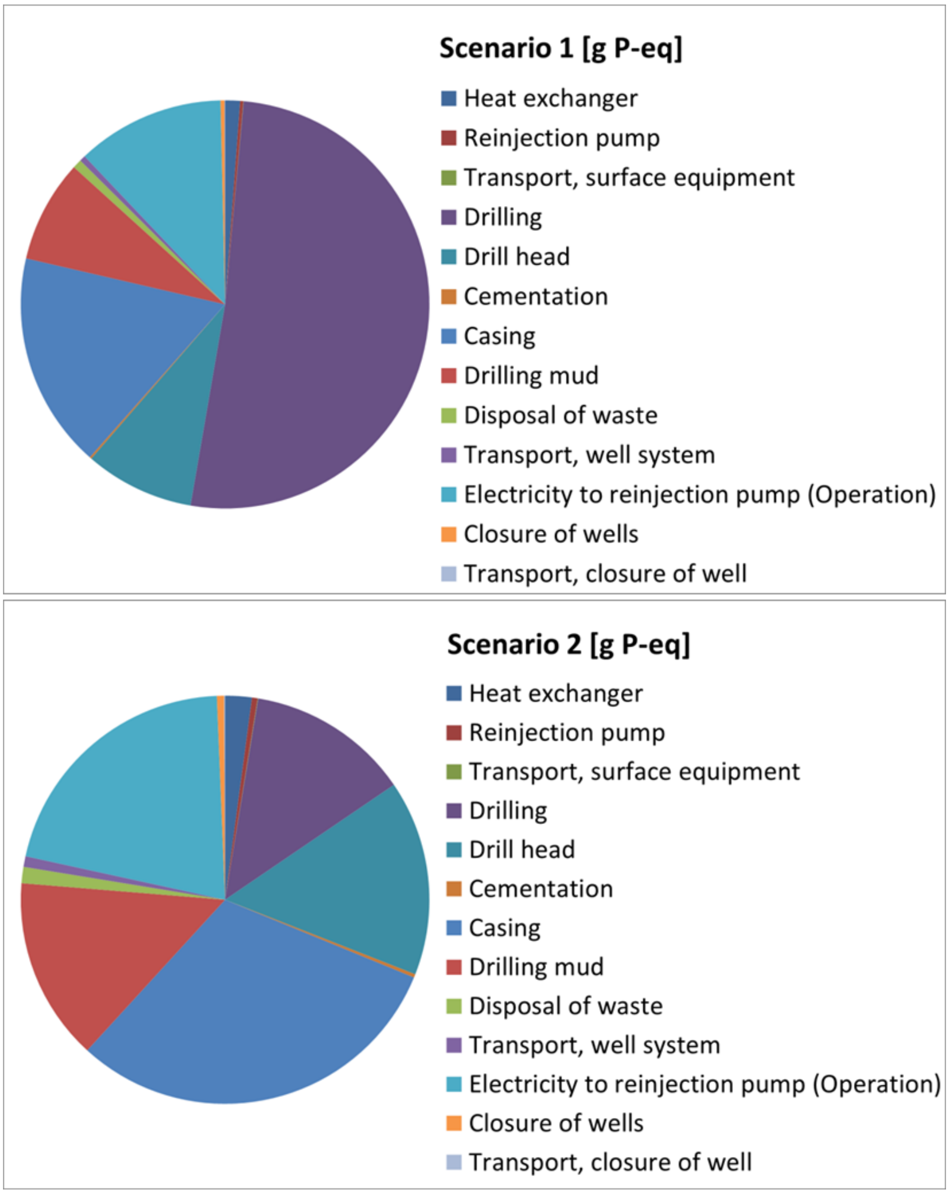


Figure 5.6 – Freshwater eutrophication results for scenario 1 and 2

Freshwater eutrophication is related to the emissions of disposal of spoil from lignite and coal mining (Appendix F, Figure 9.5 and Figure 9.20). These emissions are highly dependent on the electricity consumption during the drilling process, and are sensitive to the imported fraction of the Norwegian electricity mix. For scenario 2, where the electricity consumption is estimated to be lower, the relative contribution from drill head, casing, drilling mud, and the reinjection pump operating the plant are higher.

The absolute value of the impact category, freshwater eutrophication, is from the results expected to be in the interval of 4,527E-04 to 8,091E-04 g P-equivalents/kWh.

Terrestrial acidification

The results for terrestrial acidification are presented in Figure 5.7.

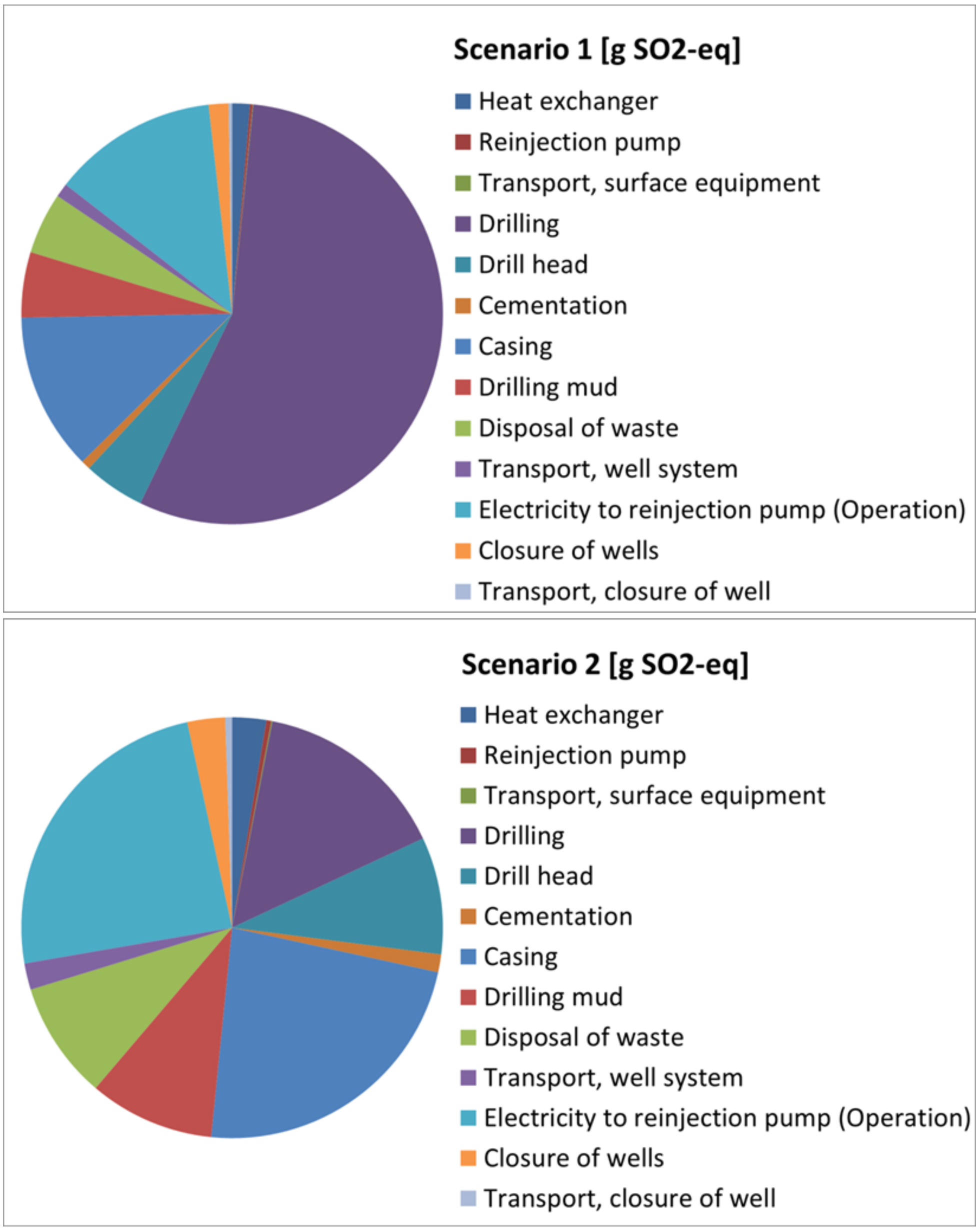


Figure 5.7 – Terrestrial acidification results for scenario 1 and 2

The results for the impact category terrestrial acidification are similar to the freshwater eutrophication results. When electricity consumption decreases, the relative importance of other contributing processes increase. Appendix F, Figure 9.6 and Figure 9.21, show how hard coal and heavy fuel oil burned in power plants contributes the most to SO_2 emissions. For the drilling process and the running of the reinjection pump, these emissions are related to the imported fraction of the Norwegian electricity mix. Emission of SO_2 is also present during extraction and production of metals and alloys, which make the casing and drill head contributing processes.

5.9.2 Sensitivity to energy source and lifetime

The results of selected impact categories are presented in the following section. The results are presented in charts where the individual subcategories' contribution is visible. To get an overview of the results the four main groups of processes (well system, surface equipment, operation and closure of wells) are presented in charts to define which process are most influent in the impact assessment. Table 5.13 summarizes the results for the investigated scenarios for a lifetime of 30 years.

Table 5.13 – Variation in energy source - Results

Effect category	Climate change	Fossil depletion	Freshwater eutrophication	Metal depletion	Terrestrial acidification
Unit/kWh	**g CO2-Eq**	**g oil-Eq**	**g P-Eq**	**g Fe-Eq**	**g SO2-Eq**
Scenario 1, electricity NO	2,1026	0,5478	0,0008	0,7173	0,0065
Scenario 1, diesel	11,64649	3,98354	0,00065	0,60315	0,01865
Scenario 1, electricity EU	23,58014	6,82351	0,02307	0,78028	0,09806
Scenario 2, electricity NO	0,9993	0,2634	0,0005	0,5871	0,0034
Scenario 2, diesel	3,8635	1,2760	0,0005	0,5763	0,0073
Scenario 2, electricity EU	7,4516	2,1488	0,0071	0,6060	0,0309

Scenario 1, with electricity provided from the European grid, is the scenario with most emissions for all impact categories evaluated. To illustrate the high emissions of this scenario, it is noted that the second worst scenario of each impact category give a decrease in emissions (relative to scenario 1, electricity from European grid) of 50,6%, 41,6%, 69,2%, 8,1% and 68,5% for the respective impact categories climate change, fossil depletion, freshwater eutrophication, metal depletion and terrestrial acidification.

The results from Table 5.13, is presented as charts in Figure 5.8 to Figure 5.12, together with the effect of increasing the lifetime of the geothermal system from 30 years to 50 years. Figure 9.2 to Figure 9.31 in Appendix F, show the background processes' impact on the results.

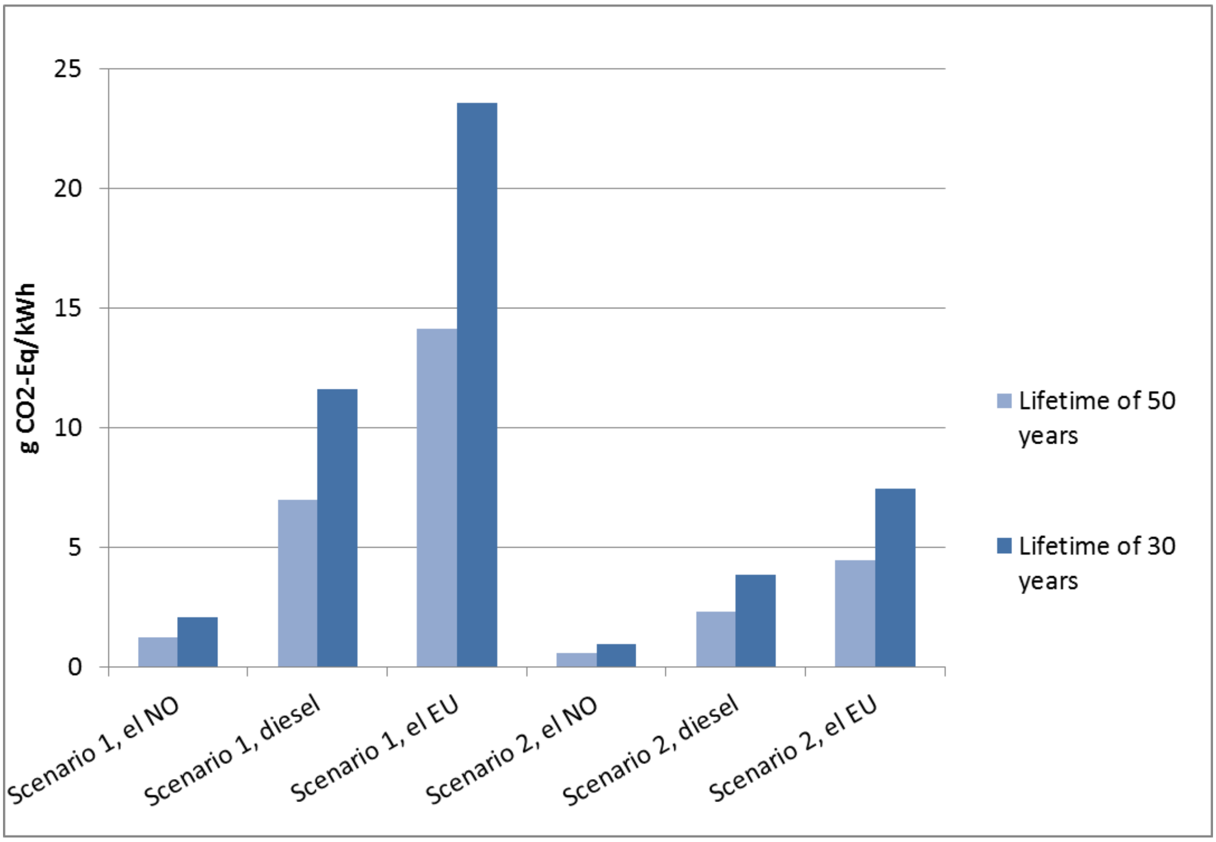


Figure 5.8 – Climate change results

The climate change category has especially been in focus when conducting the simulations and is a category of large spread in the results. For both the scenarios, the choice of energy supply has a great impact on the results. The climate change category reaches its maximum for scenario 1, where the "worst case" fuel consumption of 3,5 GJ/m and a European electricity mix is assumed. For a geothermal system in Europe, the results show that it would be advantageous to use diesel as energy supply for the drilling process compared to a European electricity mix, where the emissions are doubled. For scenario 2, the same trend can be seen. However, the energy consumption is of a smaller magnitude, and the relative impact of changing from diesel to European electricity mix is therefore smaller.

Increasing the lifetime from 30 years to 50, the contribution for each scenario is reduced by 40%.

The impact category fossil depletion is presented in Figure 5.9.

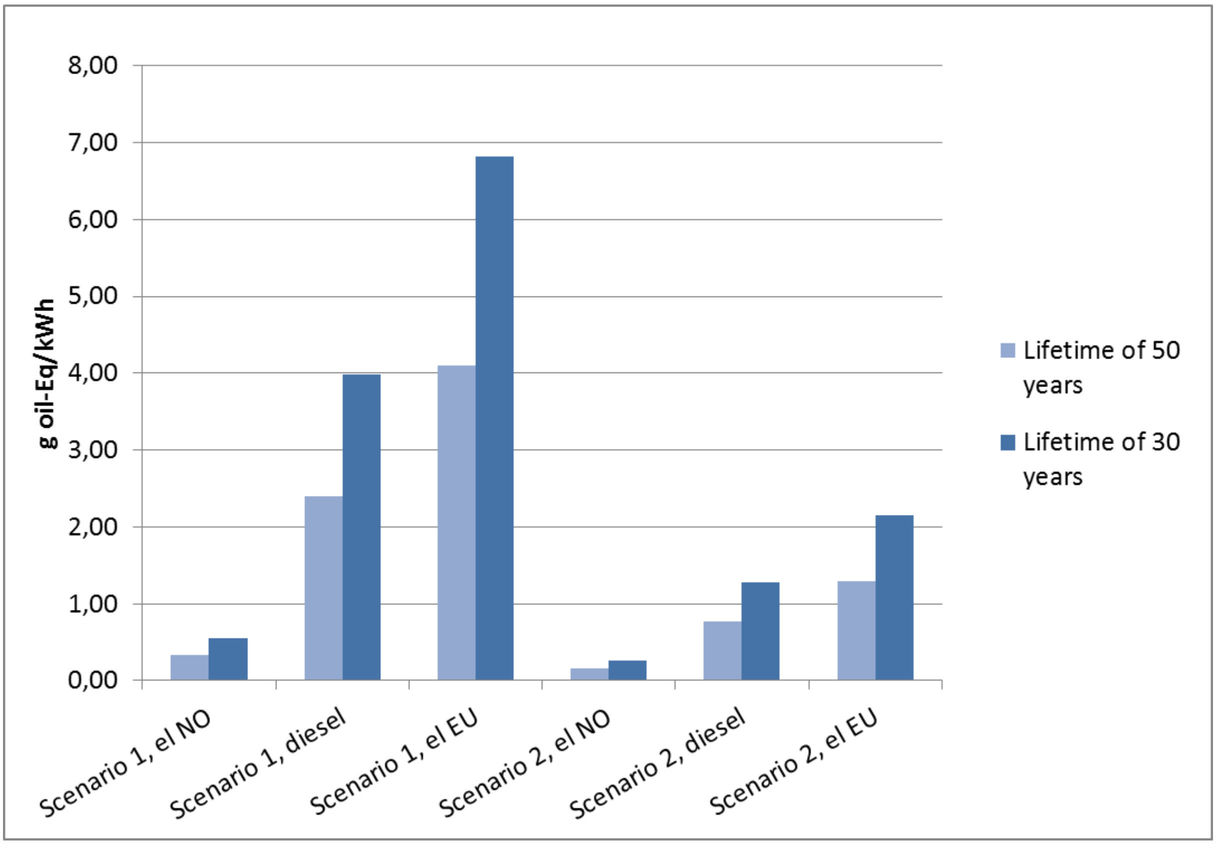


Figure 5.9 – Fossil depletion results

As for the global warming potential, scenario 1 with European electricity mix, results in the worst alternative. One can hence see that extraction and burning of coal, lignite and other electricity generating sources (see Table 5.11 for production source) has a greater impact on the fossil depletion impact category than the burning of diesel.

The results of the impact category metal depletion are presented in Figure 5.10.

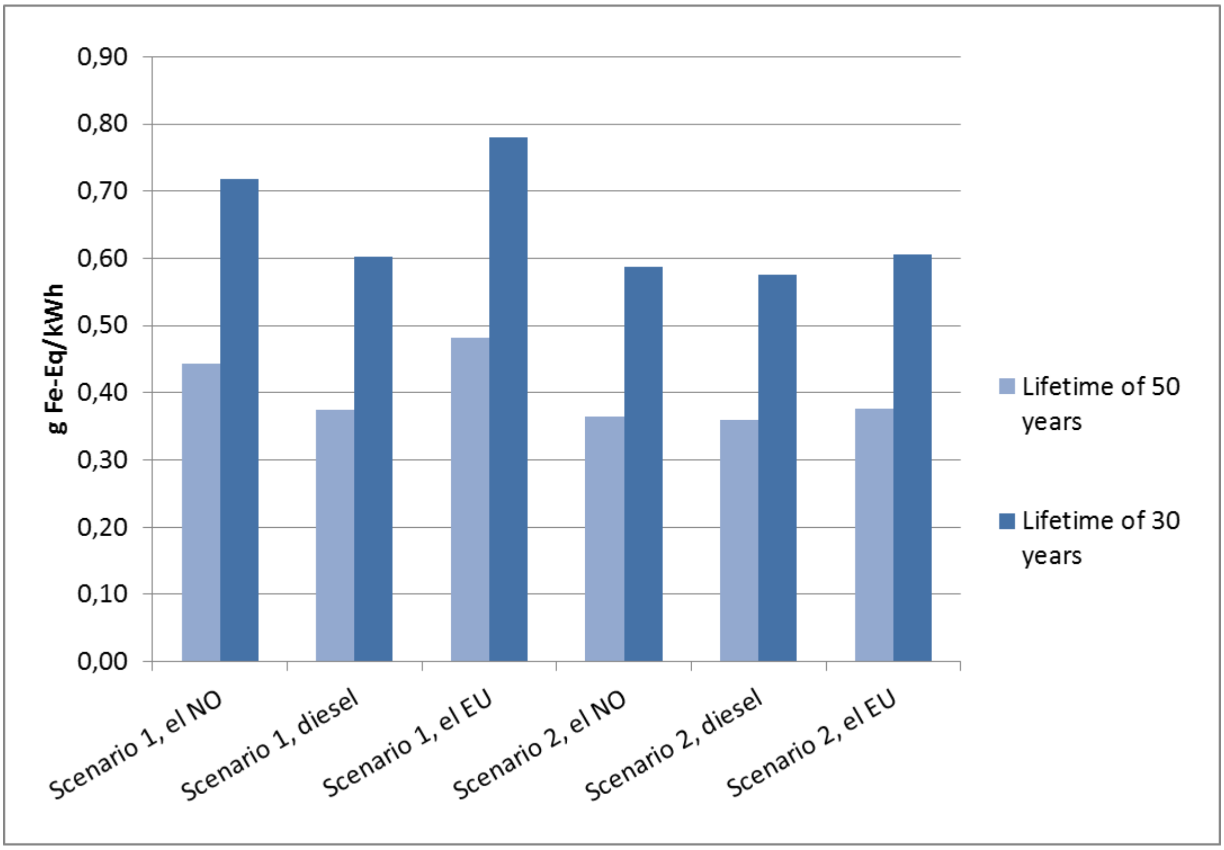


Figure 5.10 – Metal depletion results

For the metal depletion impact category, the variation of energy suppliers causes the least fluctuation of all categories assessed. This is also the only impact category where the Norwegian electricity mix has higher impacts than for the diesel consumption. This can be explained by the infrastructure related to electricity transmission.

The impact category freshwater eutrophication is presented in Figure 5.11.

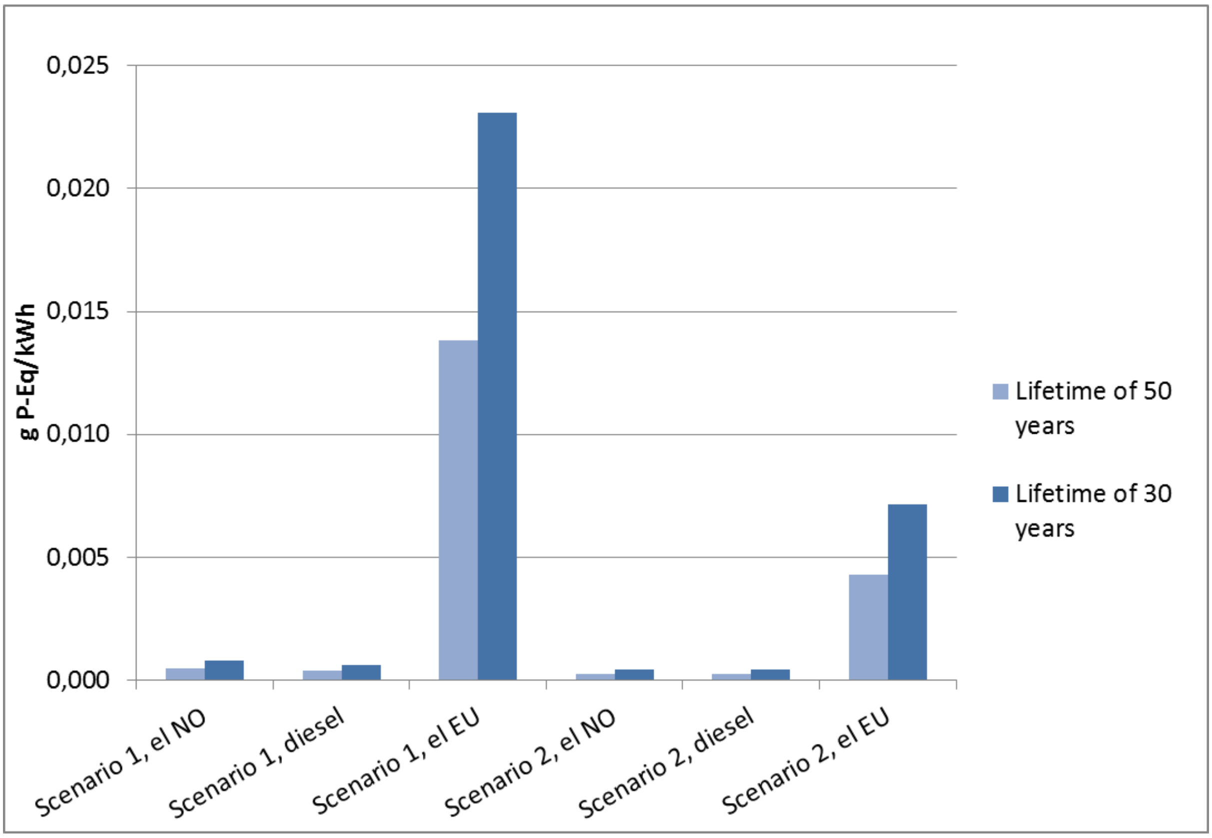


Figure 5.11 – Results freshwater eutrophication

There are mainly two scenarios that stand out with high impact on the freshwater eutrophication. The electricity depending processes in the geothermal system are mainly the drilling process for construction and the reinjection pump during 30/50 years of operation. Almost 75% of the freshwater eutrophication is due to the disposal of spoil from lignite mining (Appendix F, freshwater eutrophication for all scenarios), causing emissions of nutrients to water. Scenario 1, with Norwegian electricity mix has in relation to the European electricity mix only 3,5% of the emissions. This is as mentioned due to disposal of spoil from coal and lignite and disposal of sulfidic tailings.

The results of terrestrial acidification are presented in Figure 5.12.

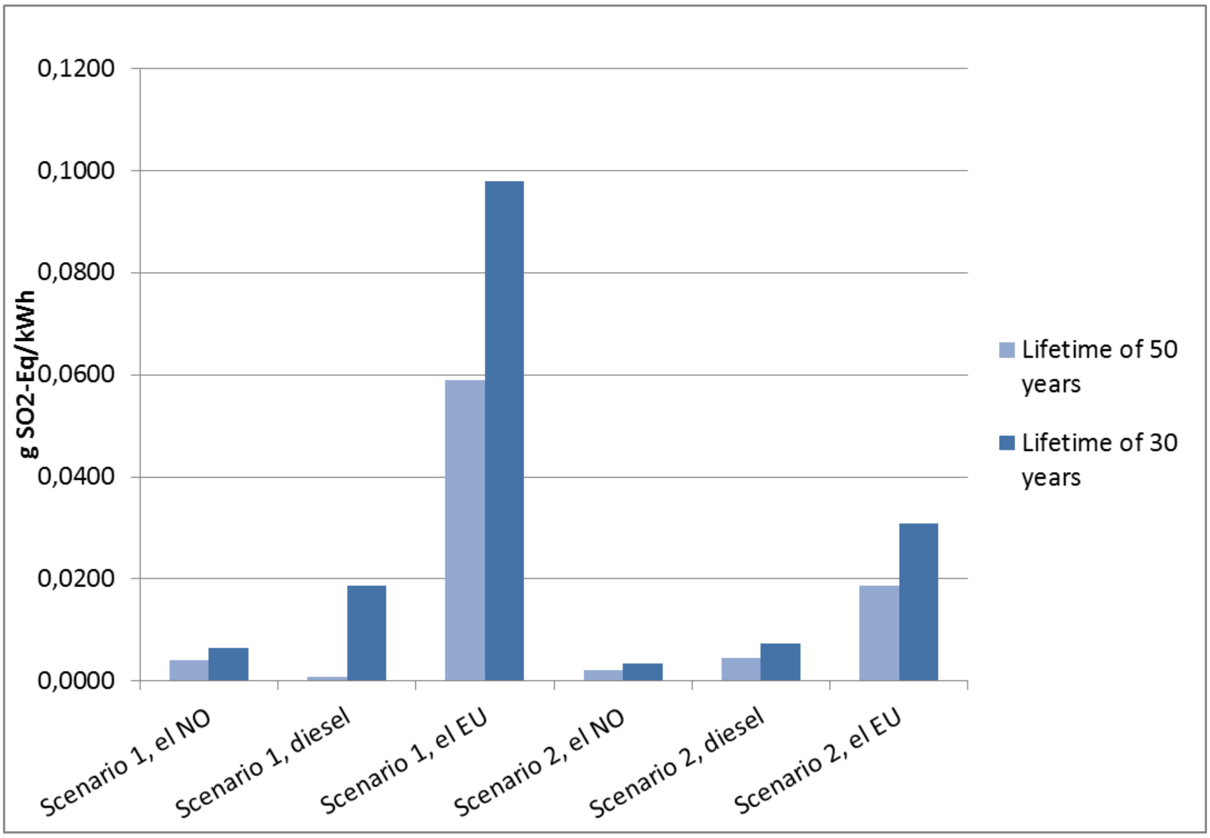


Figure 5.12 – Results terrestrial acidification

For the terrestrial acidification the results will, as for the freshwater eutrophication, be highly dependent on the electricity generating processes for a European electricity mix. Here emissions from the burning of hard coal and lignite are most decisive, contributing to an increase in acidity.

For the two scenarios where diesel is the energy supplier for the drilling process, the processes related to diesel production contributes the most to the emissions of SO_2-equivalents. The burning of natural gas in the production flare, and the heavy fuel oil burned in refinery furnace during separation, are the biggest contributors to emissions.

For the Norwegian electricity mix, the processes with highest impact are related to the imported electricity, whereas hard coal and heavy fuel oil burned in power plants contributes the most. The total impact of these scenarios is small.

Comment to the variations in lifetime

The lifetime of the geothermal installation of Rock Energy's concept cannot be determined as a constant input to the life cycle assessment as the system has not been built. The top site equipment, heat exchanger and reinjection pump, is assumed to have a lifetime of 20 and 10 years, respectively. However, the system as a whole may be in operation for 30 years or more. If the geothermal system delivers heat at a sufficient temperature for 50 years, the overall environmental effect is reduced.

Scenario 1, considering 3,5 GJ/meter energy requirement for drilling (using electricity at the Norwegian grid), with a lifetime of 50 years produces 1,27 g CO-Eq/kWh.

5.10 Comparison to existing literature

Based on Martino Lacirignola's report on the Soultz-sous-Forêts geothermal power plant [23] and two articles by Kaltchmitt, M. et al., 2000 [35] and Eriksson et al., 2007 [36], a validation of the LCA results of this report is conducted, together with a comparison to other energy suppliers to district heating.

5.10.1 Comparison to the Soultz-sous-Forêts geothermal power plant

The EGS project at Soultz-sous-Forêts is a power plant installation of 1,5 MW_e (Organic Rankine Cycle). The geology at the site is characterized by about 1500m of sedimentary layer on top of a granitic basement.

A thorough LCA assessment has been made for the project, considering both the construction of the well system and top site equipment, presented in a report by Martino Lacirignola [23].

As this analysis is constructed with a foundation of reported and measured values for energy and material demand, it works as a good source for comparison to inspect the validity of the LCA study conducted in this report.

For practical reasons, adjustments were necessary to be able to compare results of the Soultz-project, as the technical concept differs from Rock Energy's subsurface heat exchanger concept.

In short, the life cycle assessment presented by Lacirignola, is based on the following criteria.

The functional unit is kWh of net electricity produced in the life cycle. This means that all emissions calculated in the life cycle is related to the unit of electricity delivered to the national electricity grid. The net power is calculated from electrical output of the ORC minus the power required for pump production for reinjection in the geothermal loop and auxiliary power required (air condenser etc).

The "base case" for the LCA report by Lacirignola is based on the following:

3 wells of 4 km, with a water flow rate of 40 l/s. The reinjection flow rate in the wells is 20 l/s. The produced temperature is 165^oC.

Considering the climate change category, the overall absolute emission is calculated to be 36,7 g CO_2-Eq/kWh. This is based on the net power production of the plant, 1,5MW_e.

Assuming that the net efficiency of the ORC used at Soultz-sous-Forêts is somewhere between 10 and 15%, the amount of heat produced from the reservoir can be calculated based on the amount of power generated. Taken an amount of heat production of 10MW and 15MW, over a lifetime of 25 years, the amount of CO_2-equivalents is reduced. See Table 5.14.

Table 5.14 – Results of M. Lacirignola based on two assumptions for ORC efficiency

ORC efficiency	Produced heat [MW]	Climate change [g CO2-Eq/kWh]
10 %	15	3,67
15 %	10	5,51

This forms a foundation for comparison with district heating with no other conversion technology than a heat exchanger between the geothermal loop and the district heating network. Calculations for Rock Energy's concept, neglecting the cross well drilling, gives a climate change result of 2,71 g CO2-Eq/kWh. The use of drill heads is also reduced to consider only the vertical wells. This result is somewhat lower than for the Soultz site, but signals that the overall emissions of greenhouse gases are in the same order of magnitude. Notice that a simplification is done by "removing" the cross wells for Rock Energy's concept, while hydraulic stimulation of the reservoir for Soultz-sous-Forêts is still taken into account. This process requires energy input, however, not in the same order of magnitude as the drilling process. Other differences between the two concepts are top-site equipment, which is considerably more extensive in the power-production context.

5.10.2 Comparison to other literature

In this chapter the results are compared to existing literature on LCA of district heating systems utilizing alternative energy sources. Due to system differences the studies are presented shortly with the main assumptions and limitations underlying each study. The comparison of results is limited to the climate change impact category.

Two articles have been reviewed:

- *Environmental effects of heat provision from geothermal energy in comparison to other sources* by Kaltchmitt M.,2000, pp. 627-632 [35]
- *Life cycle assessment of fuels for district heating: A comparison of waste incineration, biomass- and natural gas combustion* by Eriksson et al., 2007 [36]

Kaltchmitt compares different scenarios for provision of heat to three different supply tasks: residence (installed capacity of 40kW), small district heating system (installed capacity of 3MW) and large district heating system (with an installed capacity of 10MW). The reason for using different supply tasks is that the different technologies for using renewable energy sources work at different capacity ranges. The energy sources considered are geothermal energy from soil and groundwater, geothermal energy from deep wells, geothermal energy from hydrothermal resources, solar thermal energy, biomass and fossil fuel energy. The goal of the study is comparison of different environmental impact of heat production from the different energy sources. The functional unit is 1 GJ of heat at plant gate.

As the work of this report is concerned with a geothermal installation of 10 MW it is interesting to review the results by Kaltchmitt concerning "large district heating system". The energy sources investigated by Kaltchmitt for large district heating system are limited to heat from biomass, heat from hydrothermal resources and heat from fossil fuel. It is nevertheless interesting to look at the results for "heat from solar energy" and "heat from deep wells" for small district heating systems as well.

It is worth mentioning that Kaltchmitt has a different perspective on heat from deep geothermal wells than this thesis. In the report deep geothermal energy refers to energy that can be extracted based on deep wells with a heat transferring fluid being circulated, but it is assumed that the wells are "not very deep", and the gained temperature will thus not be very high. A heat pump is required. In addition, the heat pump does only serve as base load. Peak load is typically covered by fossil fuel energy.

Solar thermal energy is assumed to only cover a small portion of heat needed for heating the living space, and it provides in most cases only sanitary hot water. A back up system with the overall thermal capacity is needed; it is assumed that this backup system is fired with fossil fuel in small district heating system.

For the use of biomass in district heating it is assumed by Kaltchmitt that plants above a few 100kW use a peak load system of fossil fuel energy. Therefore the use of biofuels is seen in combination with the use of fossil fuels for the three supply tasks. Light oil or natural gas is seen as possible fossil fuel sources, and this is the basis for investigation by Kaltchmitt.

The results of the article are presented in Table 5.15

Table 5.15 – LCA results based on Kaltchmitt [35]

	Consumption of finite energy in GJ/TJ	CO_2-Equi-valents in t/TJ	SO_2-Equi-valents in kg/TJ	sulphur dioxide (SO_2) in kg/TJ	nitrogen oxide (NO_x) in kg/TJ
"Residence"					
Heat from solar energy	992	61	61	34	38
Heat from biomass	54	5	96	27	88
Heat from soil and groundwater	723 – 817	50 – 56	67 – 79	35 – 43	42 – 48
Heat from fossil energy	1,355 – 1,503	82 – 106	72 – 223	37 – 149	50 – 105
"Small District Heating System"					
Heat from solar energy	1 007	74	185	111	105
Heat from biomass	405	29	186	49	186
Heat from deep wells	744	50	117	55	88
Heat from fossil energy	1,530 – 1,711	90 – 122	99 – 284	53 – 166	64 – 168
"Large District Heating System"					
Heat from biomass	422	30	158	49	150
Heat from hydrothermal resources	38 – 299	4 – 16	14 – 33	6 – 14	11 – 27
Heat from fossil energy	1,548 – 1,712	90 – 122	100 – 285	54 – 166	65 – 169

GJ = Giga Joule; 10^9 J; TJ = Tera Joule; 10^{12} J; t = one metric ton; kg = one kilogramme.

Eriksson et al. look at how waste incineration can be environmentally compared to other fuels in district heating or combined heat and power (CHP). The other fuels investigated are combustion of biomass and natural gas (the latter only considered for CHP). The study is comprehensive and includes "savings", meaning that the avoided electricity generation or the avoided waste management method is taken into account. The fuel chains are in themselves complex systems, and when considering the links between district heat production and other sectors such as electricity generation and waste management, it becomes even more complex. Eriksson et al. states that a fair comparison can only be conducted with the included additional consequences. This type of LCA is referred to as a "consequential LCA", where the model includes processes that are significantly affected whether inside or outside the life cycle. The study is for simplicity set to primarily concern two alternatives for marginal electricity generation (fossil lean or intense), representing two extreme cases. Alternative waste management is landfill disposal or material recovery.

The study is based on Swedish conditions, and marginal electricity of the Nordic countries is used. It is however stated that the study is not restricted to Swedish conditions, since many district heating systems can be found in many countries in northern Europe, and the problem of fuel choice is general.

The functional unit is MJ district heat produced. If the biomass (and natural gas) is *not* burned for district heating purposes, it is assumed to remain in the forest (and ground). This is specified as a significant limitation in the study, as the biomass or natural gas is likely to be extracted and used for other purposes if not used in district heating. Biomass "saved" through paper and cardboard recycling is assumed to remain in the forest.

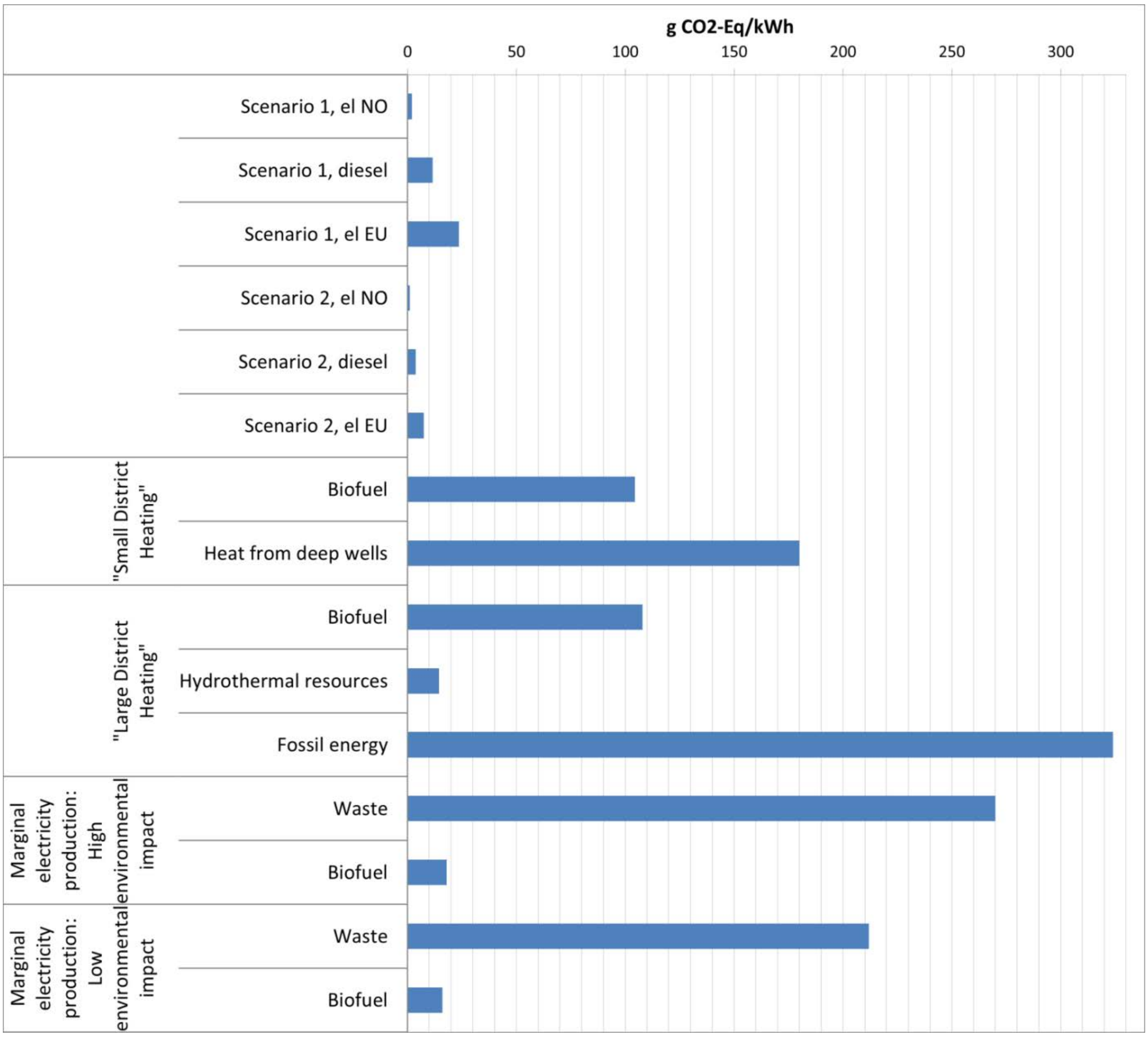


Figure 5.13 – Comparison of results

Figure 5.13 presents selected results from Kaltchmitt considered to be the most appropriate for comparison. These cases are biofuel and heat from deep wells in "Small district heating system" and biofuel, hydrothermal resources and fossil energy in "Large district heating system". From the study by Eriksson et al. only results concerning district heating are presented. These are waste incineration and biofuel for both cases concerning marginal electricity production. Waste burned in district heating is presented only for substitution to the alternative treatment material recycling. Waste incineration replacing landfill is not presented, as the results from this case cause negative impact due to very high savings of emissions. Both cases for marginal electricity production are covered in the figure (fossil lean and intense).

Scenario 1, Norwegian electricity mix and all cases of scenario 2 have the lowest environmental impact of all cases considered. Only scenario 1, diesel and European electricity, are in the same order of magnitude as results from Kaltchmitt and Eriksson et al. The results for hydrothermal resources (Kaltchmitt) and both cases of biofuel from Eriksson et al. are close to the emissions from scenarios 1, diesel and scenario 1, European electricity mix. Biofuel assessed by Kaltchmitt is considered in a closed carbon cycle, meaning that the combustion of biomass do not contribute to global warming potential because CO_2 has been removed from the atmosphere during plant growth. It is interesting to see that despite this, the emitted CO_2-equivalents are considerably higher than the CO_2 equivalents emitted for the biofuel in the study by Eriksson et al. The result may be partly defended by Kaltchmitt assuming a peak load system of fossil fuels, independent on supply task.

Waste incineration is very much dependent on the alternative waste management, although this is not presented in the figure. It is concluded by Eriksson et al. that waste incineration is the preferable choice when incineration replaces landfilling. However, the opposite is true when incineration replaces recycling. This can be seen from the figure. Emissions are close to emissions of burning fossil fuels.

The heat from deep wells by Kaltchmitt results in a relatively high emission of CO_2-equivalents compared to the results from all scenarios of this report. This is due another perspective on the available heat that can be extracted from geothermal wells. Kaltchmitt assumes that the wells are “not very deep”, and that a heat pump is required. In addition the peak load is covered by fossil fuels. The conversion factor of the heat pump, in addition to the fossil fuel combustion, results in the net thermal output provided by geothermal heat being low. In the work conducted in this report it is assumed a thermal output of 10MW with 5000 operating hours in one year. In addition, a relatively long lifetime of the plant is assumed (30 years). This contributes to the overall emission per kWh becoming low.

In addition to a high thermal output from the geothermal system of this report, the inventory collection is based on “best case” estimates. It is not taken into consideration unexpected events. Especially the drilling process is sensitive to energy consumption if the timespan for drilling increases considerably. Also, the district heating grid is left out of the system boundary. It is unknown whether or not this is considered by Kaltchmitt and Eriksson et al.

The scenarios concerning drilling with Norwegian electricity mix are the most favorable results from this comparison. In addition, the comparison indicates that Rock Energy’s conceptual geothermal system is environmentally competitive to all fuels compared, irrelevant of energy supply to the drilling process. However, it is a requirement that boundary conditions are relatively equal to be able to compare directly the emissions of different studies. Therefore a generalization based on this comparison is not possible.

It would have been interesting to compare the results of this study with district heat provision from waste and biofuel, isolated. It has however unfortunately not been found a study with the same boundary conditions as for this work.

6 Discussion and conclusion

An analysis has been conducted for the present district heating system operated by Hafslund at Oslo Airport Gardermoen, in addition to an analysis of the implementation of a geothermal base load for the extended system. The present energy production for the system is 74 GWh, which is total for the main heating central and the mobile central. The peak load of the system is found to be 25,7 MW.

For the enlargement of the plant the two centrals have been evaluated individually. The mobile central has been found most suitable for a geothermal installation. The geothermal installation will contribute with 10 MW for this central, out of the design load of 15,2 MW. Thus the geothermal installation covers approximately 65% of the required load, and 90% of the total energy production.

The mobile central is found suitable for the geothermal installation due to the grid specifications and existing installations of this central. At present this central has an installed capacity of only 2,7 MW, thus new installations are required to increase the capacity. The grid connected to this central has the capacity to handle the increase in load to 15,2 MW without restructuring.

The main heating central is also expected to increase its production within 2022 (in which design load becomes 37,4 MW). The installed capacity at present is 40,6 MW, which indicates that new installations are not absolutely necessary (neglecting redundancy for the system). It is therefore considered, from an environmental perspective, unwise to replace any boilers in this central with geothermal energy, as the base load is already covered by biofuel. The grid connected to the heating central is found to be a limiting component when considering the increased production. The increase in production must be implemented by either an increase of ΔT in the system, or an increase in mass flow. If choosing to increase the mass flow of the system, keeping ΔT constant, the general recommended limit for water velocity in the grid is exceeded. ΔT can be increased only if the local components (radiators etc.) are replaced, as these are designed for a certain temperature range. It is clear that measures must be taken for the grid and/or local components to cope with the increased production.

It has been conducted an environmental analysis for Rock Energy's conceptual geothermal system to identify the contributing processes to climate change, fossil depletion, metal depletion, freshwater eutrophication and terrestrial acidification. The energy consumption for drilling purposes is considered a source of great uncertainty, yet an important contributor to environmental impact, therefore this input has been divided into scenarios. In scenario 1 the energy consumption for drilling is assumed to be 3,5 GJ/m, which is based on reported values for drilling geothermal wells at the Soultz-sous-Forêts site on the border between France and Germany. For scenario 2, the energy consumption is based on calculations conducted with basis in information given by drilling experts and Rock Energy. This calculation resulted in an energy consumption of 0,482 GJ/m and 0,375 GJ/m for the vertical and cross wells, respectively. Energy sources for drilling that have been considered are electricity from the Norwegian grid, electricity from the European grid and from diesel.

The results from the LCA confirm that the drilling process has a significant impact on climate change, fossil depletion, freshwater eutrophication and terrestrial acidification. The metal depletion category is not greatly affected by the drilling process. The main contributors to this category are casing and drill head.

Scenario 2, with electricity provided from the Norwegian grid, is the best scenario relative to the other scenarios when it comes to the climate change category, with emissions of modest 0,9993 g CO_2-eq/kWh. Scenario 1, with electricity from the European grid, is the worst alternative with emissions up to 23,6 g CO_2-eq/kWh. Scenario 2, with electricity from the Norwegian grid, is also the category of lowest emissions for the categories fossil depletion, terrestrial acidification and freshwater eutrophication. From an overall evaluation of the impact categories assessed in this report, it is therefore this scenario that will give the lowest environmental impact.

The metal depletion category is the only category where scenario 2, with electricity from the Norwegian grid, does not have the lowest environmental impact. Scenario 2, with diesel as energy source, is the best scenario for this category. The reason why electricity causes more impact on the metal depletion category is due to the infrastructure of the electricity transmission network being accounted for in the analysis.

Scenario 1, with electricity provided from the European grid, is the scenario with most emissions for all impact categories evaluated. To illustrate the high emissions of this scenario, it is noted that the second worst scenario of each impact category give a decrease in emissions (relative to scenario 1) of 50,6%, 41,6%, 69,2%, 8,1% and 68,5% for the respective impact categories climate change, fossil depletion, freshwater eutrophication, metal depletion and terrestrial acidification. If the geothermal concept of Rock Energy were to be implemented on continental Europe, it would from an environmental perspective be advantageous to use diesel for the drilling process.

The results are compared to existing life cycle assessments conducted for an enhanced geothermal system (EGS), a hydrothermal system, and district heating with biofuels, waste incineration and fossil fuel combustion.

The comparison indicates that Rock Energy's conceptual geothermal system is environmentally competitive to all compared fuels for district heating, irrelevant of which energy supplier is used for the drilling process. It is however a prerequisite when comparing life cycle assessments on energy provision systems that the system boundaries of the studies compared are relatively equal. This is not the case for the studies compared. Therefore a generalization based on this comparison is not possible. It has unfortunately not been found a study with the same boundary conditions as for this work.

7 Further work

This chapter presents the proposals on topics that should be evaluated for further work, based on the established analysis for the district heating system at Oslo Airport Gardermoen and the system model for LCA.

7.1 Technical evaluation of equipment

The dimensions of the grid at the heating centrals operated by Hafslund have been evaluated when considering the centrals' capacity increase. It is however important to evaluate other components in the system, such as the additional pump capacity for circulation of the water, the valves controlling the mass flow, the regulation system etc. The entire physical system must be mapped to make sure that components do not cause restriction for the increased capacity.

7.2 Economical evaluation

The economic cost of the enlargement of the heating centrals has not been considered in this report. An economic evaluation of the designed geothermal system for the mobile central should be performed, estimating the cost of heat. It should in turn be compared to the cost of other potential heat sources that can be implemented in the central. Also, the cost of restructuring the grid and/or implementing new local installations (radiators etc.) for the heating central should be performed to ensure cost efficiency of the enlargement.

7.3 Expand system boundaries

It is mentioned several times in the report that an LCA is based on a model of a system which often is a simplification of reality. In this case, it means that the district heating grid, drilling rig and demolition/recycling of surface equipment is not included in the analysis. Inclusion of these aspects will contribute to increase the validity of the results, thus creating a better foundation for decision-making.

7.4 Change in assumptions

Input data concerning material extraction and processing is gathered from the database Ecoinvent for this report. When data was not found for a particular process in Norway, it was replaced with the most representative process valid for Europe. An example of this is the steel used in casing. The input from Ecoinvent for this material is based on a mix of differently produced steels, which represents average world and European production mix. It is unknown what recycling rates and production mix are common for steel in Norway. These assumptions may therefore affect the results and should be investigated more thoroughly to increase the validity of the results.

7.5 Evaluate total heat and electricity production and demand in Norway

The implementation of a new heat provision technology in Norway may displace some of the current technologies for heat and electricity production. Recognizing that Norway have large amounts of renewable energy, the overall impact on energy production in Norway should be analyzed to get an overview of the total environmental gain (or the opposite) of introducing geothermal energy in to the Norwegian energy market.

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9 Appendix

Appendix A – Map of Gardermoen area

Appendix B – Suggestions for reinjection pump and heat exchangers

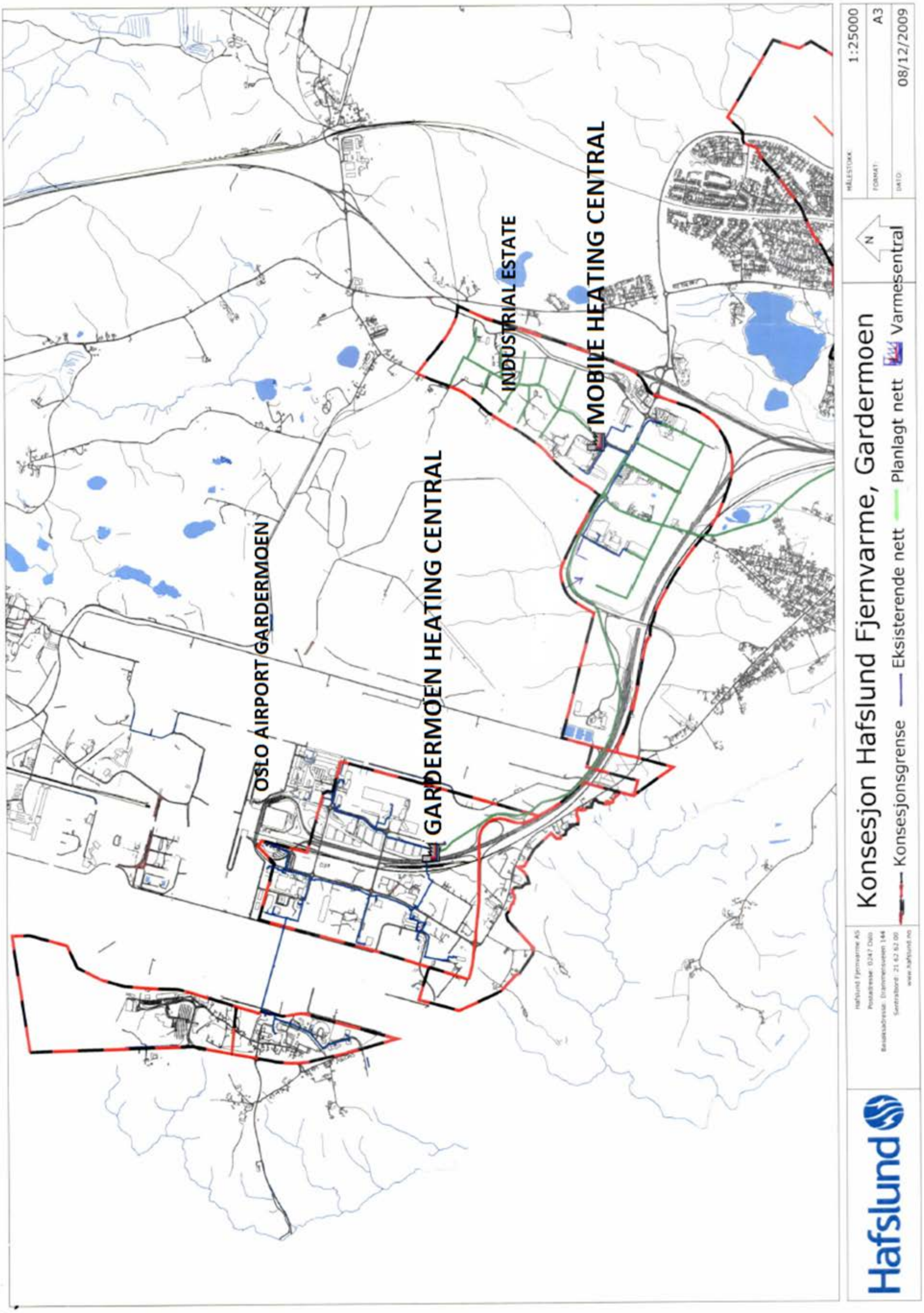
Appendix C – Flow sheet based on Frick. et al.

Appendix D – Matlab calculation models

Appendix E – Input to calculation models

Appendix F – Results of background processes' contribution to the results

Appendix A – Map of Gardermoen area



Appendix B –Suggestions for reinjection pump and heat exchangers

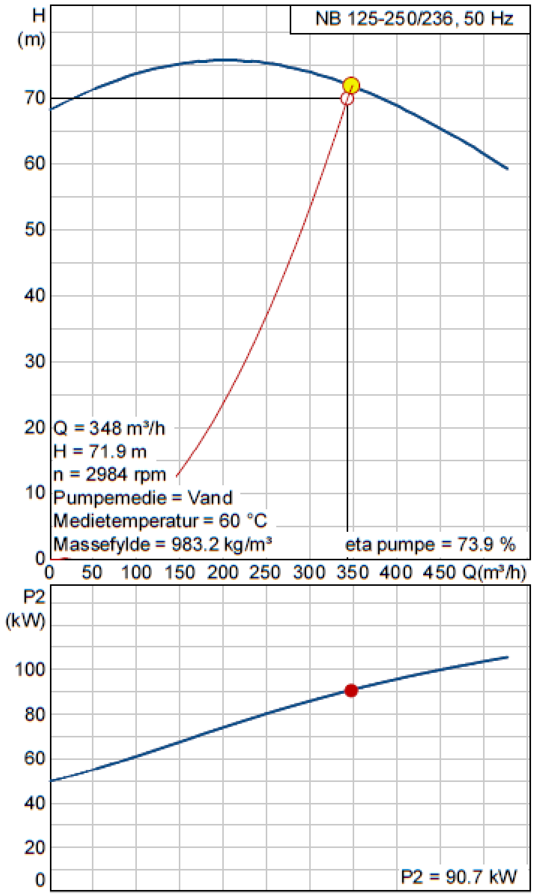
Positionsnr.	Antal	Beskrivelse	Stykpris
	1	**NB 125-250/236 A-F-A-BAQE**	Pris på foresp.
		 **OBS: Produktbilledet kan afvige fra det faktiske produkt**	
		Produktnr.: 95109708	
		Normalsugende, ettrins-centrifugalpumpe til pumpning af rene, tyndtflydende eller lettere forurenede, ikke-aggressive væsker uden slidende eller langfibrede faststoffer.	
		Pumpen er direkte koblet med en 3-faset AC-motor med IEC-flange.	
		Løberen er hydraulisk samt dynamisk aflastet.	
		Komplet enhed bestående af pumpe, fodplade, koblingsskærm og elektromotor.	
		Væske: Væsketemperaturområde: 0 .. 120 °C Medietemp.: 60 °C Massefylde: 983.2 kg/m³	
		Teknisk: Hastighed for pumpedata: 2980 omdr/min Aktuel beregnet flow: 348 m³/h Resultat for pumpens løftehøjde: 71.9 m Aktuel løberdiameter: 236 mm Akseltætning: BAQE Sekundær akseltætning: NONE Max. driftstryk.: 16 bar	
		Materialer: Pumpehus: Støbejern EN-GJL-250 ASTM A48-40 B Løber: Støbejern EN-GJL-200 ASTM A48-30 B	
		Installation: Maks. omgivelsestemperatur: 40 °C Max. driftstryk.: 16 bar Flange standard: EN 1092-2 Pumpeindløb: DN 150 Pumpeudløb: DN 125 Tryktrin: PN16	
		Elektriske data: Motortype: SIEMENS Virkningsgradsklasse: NA Antal poler: 2 Mærkeeffekt - P2: 110 kW Netfrekvens: 50 Hz	

Udskrift fra Grundfos CAPS 1/6

Positionsnr.	Antal	Beskrivelse		Stykpris
		Mærkespænding:	3 x 380-415D/660-690Y V	
		Mærkestrøm:	182/105 A	
		Startstrøm:	690 %	
		Cos phi - effektfaktor:	0,91	
		Nominel hastighed:	2980 omdr/min	
		Motorvirkningsgrad ved fuldlast:	95,8 %	
		Motorvirkningsgrad ved 3/4 belastning:	95,7 %	
		Kapslingsklasse (IEC 34-5):	55	
		Isolationsklasse (IEC 85):	F	
		Smøremiddeltype:	Grease	
		Andre:		
		Nettovægt:	988 kg	
		Bruttovægt:	1220 kg	
		Shippingvolumen:	3.84 m³	

Udskrift fra Grundfos CAPS 2/6

Beskrivelse	Værdi
Produktnavn:	NB 125-250/236 A-F-A-BAQE
Prod. nr.:	95109708
EAN nummer:	5700836490116
Teknisk:	
Hastighed for pumpedata	2980 omdr/min
Aktuel beregnet flow:	348 m³/h
Resultat for pumpens løftehøjde:	71.9 m
Aktuel løberdiameter:	236 mm
Akseltætning:	BAQE
Sekundær akseltætning:	NONE
Akseldiameter:	42 mm
Max. driftstryk.	16 bar
Pumpeversion:	A
Materialer:	
Pumpehus:	Støbejern
	EN-GJL-250
	ASTM A48-40 B
Løber:	Støbejern
	EN-GJL-200
	ASTM A48-30 B
Materialekode:	A
Installation:	
Maks. omgivelsestemperatur:	40 °C
Max. driftstryk.	16 bar
Flange standard:	EN 1092-2
Tilslutning - kode:	F
Pumpeindløb:	DN 150
Pumpeudløb:	DN 125
Tryktrin:	PN16
Spaltering(e):	spaltetætningsring(e)
Væske:	
Væsketemperaturområde	0 .. 120 °C
Medietemp.:	60 °C
Massefylde:	983.2 kg/m³
Elektriske data:	
Motortype:	SIEMENS
Virkningsgradsklasse:	NA
Antal poler:	2
Mærkeeffekt - P2:	110 kW
Netfrekvens:	50 Hz
Mærkespænding:	3 x 380-415D/660-690Y V
Mærkestrøm:	182/105 A
Startstrøm	690 %
Cos phi - effektfaktor:	0,91
Nominel hastighed:	2980 omdr/min
Motorvirkningsgrad ved fuldlast:	95,8 %
Motorvirkningsgrad ved 3/4 belastning:	95,7 %
Kapslingsklasse (IEC 34-5):	55
Isolationsklasse (IEC 85):	F
Motorbeskyttelse:	PTC
Motornr.:	83A15444
Motorprogram:	Premium
Monteringsdesign iht. IEC 34-7	IM B35
Smøremiddeltype:	Grease
Andre:	
Nettovægt:	988 kg
Bruttovægt:	1220 kg
Shippingvolumen:	3.84 m³



Udskrift fra Grundfos CAPS 3/6

GEA Heat Exchangers • (GEA Process Engineering A/S) • Nørskovvej 1b • DK 8660 Skanderborg

GEA Westfalia Separator Norway AS
Mr. Moxnes
Gjerdrumsvei 12
0484 Oslo
Norway

GEA Heat Exchangers

30.04.2012

OFFER - No. 3058257129

Your inquiry:
Your contact: Mr. Moxnes,
Tel.:0047 / 22021600, Fax: 22021601

Our Contact: Carsten Jensen,
Tel.: +45 23 27 90 12 / Fax: +45 70 15 22 44,
e-mail: carsten.jensen@gea.com

Dear Sirs,

we thank you for your inquiry. We would like to make the following offer with express reference to our attached conditions for the delivery of machines and components for domestic and export sales in their currently valid version. These conditions can also be viewed under www.gea-phe.com

Offer value:	**See page 2**
Payment terms:	30 days after date of invoice, net cash.
Terms of pricing:	freight & packing invoiced, not unloaded
Delivery time ex works:	is approx. 8 weeks after receipt of the technically (e.g. drawing approval) and commercially clarified written order. Subject to prior sales.
Delivery terms:	Price CPT- Carriage paid to (acc. to incoterms 2010). Named place of destination: Sarstedt Germany
Validity:	Our offer is valid for 1 month.

As far as our delivery item's specifications are binding they shall solely be deemed as an ordinary agreement on quality features. By no means they shall be considered as warranted characteristics in the sense of § 443 German Civil Code. The empowerment to agree warranted characteristics for delivery items is strictly reserved to our authorized representatives in the terms of §§ 48-53 German Commercial Code ("Prokuristen") and to our managing directors.

We hope that our quotation meets your requirements and are looking forward to receiving your order.

Yours faithfully,

GEA Heat Exchangers

GEA Heat Exchangers

Nørskovvej 1b, Dk-8660 Skanderborg, Denmark
Bank Account Danske Bank
VAT: DK10050715
DKK IBAN DK8230004183098098 - SWIFT DABADKKK
EUR IBAN DK9730003345718362 - SWIFT DABADKKK

Offer 3058257129 Customer: GEA Westfalia Separator Nordic AS

Customer:	GEA Westfalia Separator Nordic AS				
Quotation-No.:	3058257129	**Inquiry-No.:**			
Contact:	Jensen		**Item:** 10	**Alternative:**	0
Customer Item:			**Date:**	10/06/2012	

Item Price: 55.500,00 Euro **Total Item Price:** 55.500,00 Euro **Amount:** 1

GEA ECOFLEX Plate Heat Exchanger: NT250M B-6

Thermal data for 1 unit(s) in parallel and 1 unit(s) in series

	hot side	cold side	
Media:	Water	Water	
Media group acc. PED 97/23/EC:	Group 2 - others	Group 2 - others	
Heat exchanged:	9958,35		kW
Mass flow:	342720	342893	kg/h
Volume flow:	350,75	350,55	m³/h
Temperature inlet:	82,00	55,00	°C
Temperature outlet:	57,00	80,00	°C
Pressure drop:	136,249	136,884	kPa
Working pressure inlet:	5,00	5,00	barg

Product properties

Density:	977,10	978,17	kg/m³
Heat capacity:	4184,18	4182,07	J/kgK
Thermal conductivity:	0,66110	0,65957	W/mK
Dyn. viscosity inlet:	0,346	0,502	cP
Dyn. viscosity outlet:	0,486	0,354	cP

Unit Data

Plate Type:	NT250M H			
Heat transfer area (total / per unit):	704,40	704,40		m²
Number of plates (total / per unit):	589	589		
Plate thickness:	0,50			mm
LMTD:	2,00			K
Surface margin:	0,4			%
Plate material:	AISI316			
Gasket material / Gasket type:	NBR	glueless		
Internal flow (passes x channels):	3 x 98	3 x 98		
No. of frames (par. / ser. / total):	1	1	1	
Frame material und surface:	S355J2+N (alternative: S355 J2+N)	painted	RAL5002	

The connection types and positions are defined in the attached dimension sheet.

Design temperature:	**Min.:**	0,00 / 0,00	**Max.:**	82,00 / 82,00	°C
Design pressure:	**Min.:**	0,00 / 0,00	**Max.:**	5,00 / 5,00	barg

Test pressure: 6,50 / 6,50 barg **Design code:** PED 97/23/EC AD-2000 Checkfactor 1.3

PED category: Art.3, Abs. 3, , Normal

Conformity assessment diagram: Medium innocuous and steam pressure at Tdesign> 0.5 barg

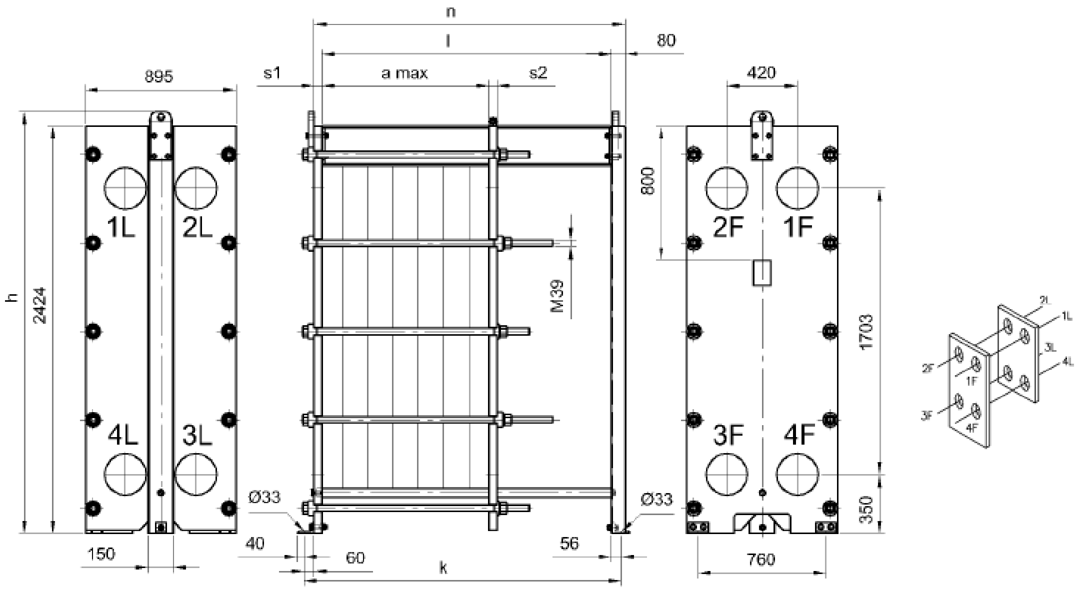
Remarks:

Offer 3058257129 Customer: GEA Westfalia Separator Nordic AS

Dimension Sheet Plate Heat Exchanger

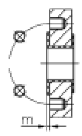
Customer:	GEA Westfalia Separator Nordic AS		
Quotation:	**3058257129**	**Item No.: 10**	**Alternative No.: 0**
Customer item:			

Type: NT250M B-6 Dimensions of drawing in [mm] 0250-141-Layout1.tif



n:	3865 mm	s_1:	45,00 mm	a-max frame:	2345 mm	empty weight:	5296 kg
k:	3901 mm	s_2:	45,00 mm	a-max actual:	2150 mm	max. total weight:	7621 kg
l:	3740 mm	h:	2569 mm				

Pos	Size	Type	Media	In	Out	Add.	m
1F	10"	Rubber insert ANSI 150 NBR 10" 0,049	Water	x	-	-	4 mm
2F	10"	Rubber insert ANSI 150 NBR 10" 0,049	Water	-	x	-	4 mm
3L	10"	Rubber insert ANSI 150 NBR 10" 0,049	Water	x	-	-	4 mm
4L	10"	Rubber insert ANSI 150 NBR 10" 0,049	Water	-	x	-	4 mm

			
Rubber insert			
ANSI150			
NBR			
1F;2F;3L;4L			

Technical Revisions reserved. Layer thickness in case of painted frames acc. DIN EN ISO 12944-5, frame plate surface quality acc. DIN EN 10029. The design details are valid for phe manufactured by GEA Ecoflex GmbH/Sarstedt.

Offer 3058257129 Customer: GEA Westfalia Separator Nordic AS

Customer:	GEA Westfalia Separator Nordic AS					
Quotation-No.:	3058257129	**Inquiry-No.:**				
Contact:	Jensen		**Item:**	20	**Alternative:**	0
Customer Item:			**Date:**		10/06/2012	

Item Price: 20.000,00 Euro **Total Item Price:** 20.000,00 Euro **Amount:** 1

GEA ECOFLEX Plate Heat Exchanger: NX150X B-10

Thermal data for 1 unit(s) in parallel and 1 unit(s) in series

	hot side	cold side	
Media:	Water	Water	
Media group acc. PED 97/23/EC:	Group 2 - others	Group 2 - others	
Heat exchanged:	9958,35		kW
Mass flow:	342720	285980	kg/h
Volume flow:	350,75	291,81	m³/h
Temperature inlet:	82,00	49,00	°C
Temperature outlet:	57,00	79,00	°C
Pressure drop:	69,048	48,829	kPa
Working pressure inlet:	5,00	5,00	barg

Product properties

Density:	977,10	980,01	kg/m³
Heat capacity:	4184,18	4178,62	J/kgK
Thermal conductivity:	0,66110	0,65675	W/mK
Dyn. viscosity inlet:	0,346	0,554	cP
Dyn. viscosity outlet:	0,486	0,358	cP

Unit Data

Plate Type:	NX150X HV			
Heat transfer area (total / per unit):	290,70		290,70	m²
Number of plates (total / per unit):	287		287	
Plate thickness:	0,40			mm
LMTD:	5,10			K
Surface margin:	0,0			%
Plate material:	AISI316			
Gasket material / Gasket type:	NBR		glueless	
Internal flow (passes x channels):	1 x 143	1 x 143		
No. of frames (par. / ser. / total):	1	1	1	
Frame material und surface:	S355J2+N alternative: S355 J2+N	painted	RAL5002	

The connection types and positions are defined in the attached dimension sheet.

Design temperature:	**Min.:**	0,00 / 0,00	**Max.:**	82,00 / 82,00	°C
Design pressure:	**Min.:**	0,00 / 0,00	**Max.:**	5,00 / 5,00	barg

Test pressure: 6,50 / 6,50 barg **Design code:** PED 97/23/EC AD-2000 Checkfactor 1.3

PED category: Art.3, Abs. 3, , Normal

Conformity assessment diagram: Medium innocuous and steam pressure at Tdesign> 0.5 barg

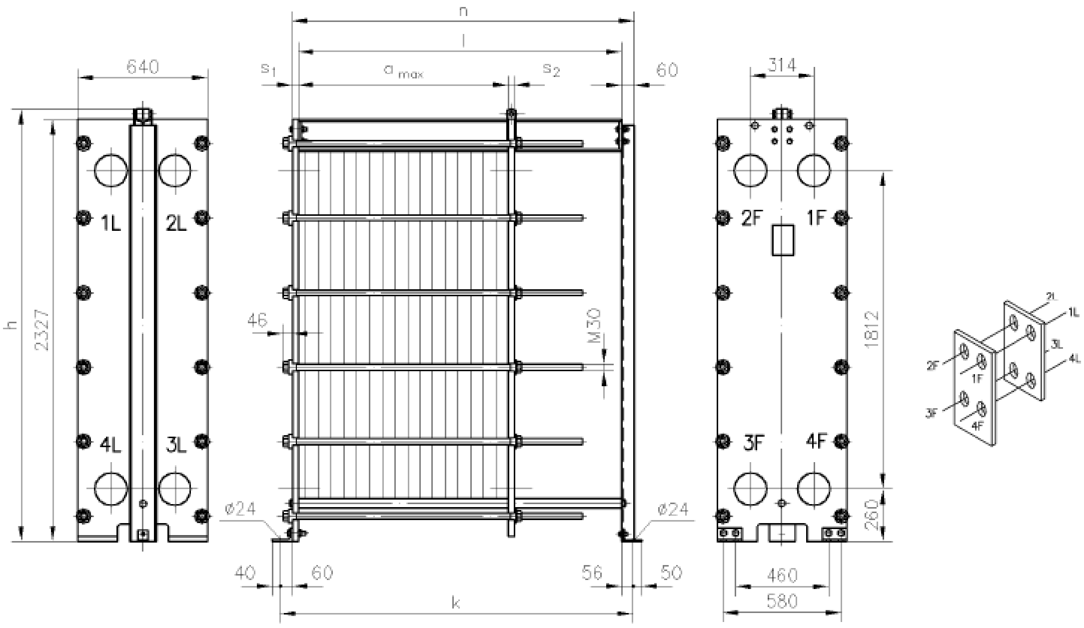
Remarks:

Offer 3058257129 Customer: GEA Westfalia Separator Nordic AS

Dimension Sheet Plate Heat Exchanger

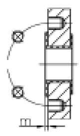
Customer:	GEA Westfalia Separator Nordic AS		
Quotation:	**3058257129**	**Item No.: 20**	**Alternative No.: 0**
Customer item:			

Type: NX150X B-10 Dimensions of drawing in [mm] 0150-132-Model.tif



n:	2040 mm	s_1:	40,00 mm	a-max frame:	949 mm	empty weight:	2060 kg
k:	2096 mm	s_2:	40,00 mm	a-max actual:	818 mm	max. total weight:	2699 kg
l:	1940 mm	h:	2377 mm				

Pos	Size	Type	Media	In	Out	Add.	m
1F	DN150	Rubber insert DIN 2633 NBR DN150	Water	x	-	-	4 mm
2F	DN150	Rubber insert DIN 2633 NBR DN150	Water	-	x	-	4 mm
3F	DN150	Rubber insert DIN 2633 NBR DN150	Water	x	-	-	4 mm
4F	DN150	Rubber insert DIN 2633 NBR DN150	Water	-	x	-	4 mm

 m			
Rubber insert			
DIN2633			
NBR			
PN16			
1F;2F;3F;4F			

Technical Revisions reserved. Layer thickness in case of painted frames acc. DIN EN ISO 12944-5, frame plate surface quality acc. DIN EN 10029. The design details are valid for phe manufactured by GEA Ecoflex GmbH/Sarstedt.

Appendix C – Flow sheet based on Frick et al.

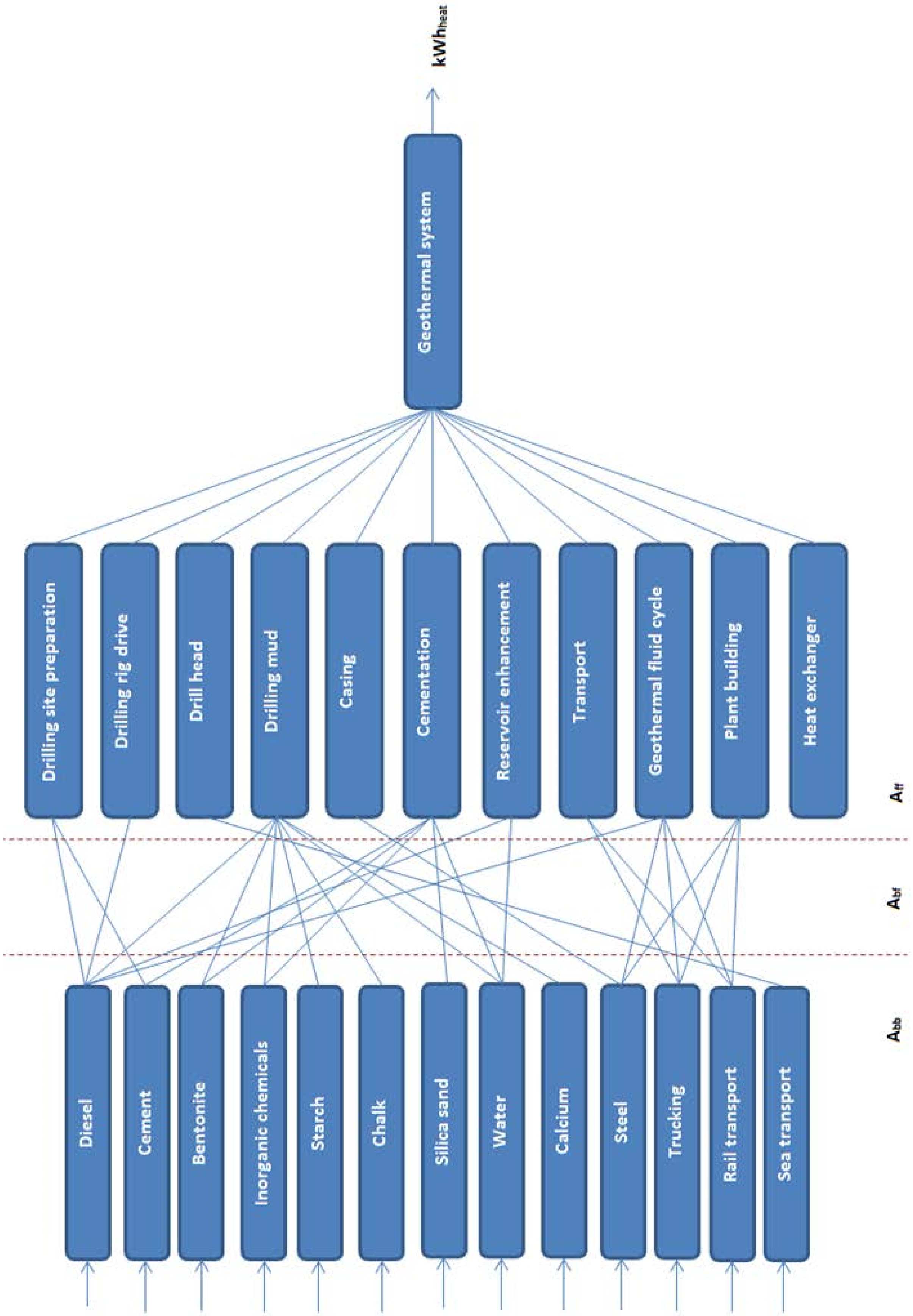


Figure 9.1 – Flow sheet based on Frick et. al.

Appendix D – Matlab calculation models

Model 1 – Hydraulic energy for mud pump

```
function Pump
clear all

% Cf inn (INNER PIPE):

mflow1=[36:6:60]

for ij=1:length(mflow1)

mflow=mflow1(ij);

%mflow=50;
visc=0.001;
Di=0.0714375;
Dy=6.5*0.0254;
Dy2=6.5*0.0254;
Do=0.3175;

visc_cutting=1;
e=0.002;
Rho_water = 1000;
Rho_cutting= 1500;

[v_inner,  v_annular,  cf1,  cf2]=  precalc  (Di,  Do,Rho_cutting,Rho_water,
mflow, visc,visc_cutting, e);

% Constants needed for further calculation

N=21;
Length_cross=2138;
%x=1374;
Depth = 4914;
Total_drilling=(Depth)+(Length_cross);
L0=27;
ROP=25/3600;

%L=[1:L0:Total_drilling];

L1 = [1:L0:Depth];
L2 = [L1(end):L0:Total_drilling];

clear deltaP1_vertical deltaP2_vertical  Energy1_vertical Energy2_vertical
Energy_cuttings_vertical

for i=1:length(L1)

    Di=0.0714375;
    Do=0.3175;
    [v_inner,         v_annular,         cf1,         cf2]=         precalc
(Di,Dy,Do,Rho_cutting,Rho_water,
    mflow, visc, visc_cutting, e);
```

```
    deltaP1_vertical(i) = (4*cf1*L1(i)*Rho_water*(v_inner^2))/2;

    deltaP2_vertical(i) = (4*cf2*L1(i)*Rho_cutting*(v_annular^2))/2 ;

    Energy1_vertical(i)=((mflow/Rho_water)*deltaP1_vertical(i)/0.85)*L0/T;
    Energy2_vertical(i)=((mflow/Rho_water)*deltaP2_vertical(i)/0.85)*L0/T;
    Energy_cuttings_vertical(i) = L0*((Do/2)^2 )*pi*2600*9.81*L1(i);

end

sum(deltaP1_vertical);
sum(deltaP2_vertical);

EnergyTot_vertical(ij)=(sum(Energy1_vertical)+sum(Energy2_vertical)+sum(Ene
rgy_cuttings_vertical))*2;

EnergyVertical_meter(ij)=(EnergyTot_vertical(ij)/(3600*1000*Depth*2))  ;

clear    deltaP1_cross    deltaP2_cross    Energy1_cross    Energy2_cross
Energy_cuttings_cross

for j=1:length(L2)

    Di=0.0714375;
    Do=0.2159;
    [v_inner,     v_annular,     cf1,     cf2]=     precalc     (Di,Dy2,
Do,Rho_cutting,Rho_water,
    mflow, visc, visc_cutting, e);

    deltaP1_cross(j) = (4*cf1*L2(j)*Rho_water*(v_inner^2))/2;

    % Pressure drop drill collar cross wells

    deltaP2_cross(j) = (4*cf2*L2(j)*Rho_cutting*(v_annular^2))/2;

    Energy1_cross(j)=((mflow/Rho_water)*deltaP1_cross(j)/0.85)*L0/T;
    Energy2_cross(j)=((mflow/Rho_water)*deltaP2_cross(j)/0.85)*L0/T;

    Energy_cuttings_cross(j) = L0*((Do/2)^2 )*pi*2600*9.81*L1(j);  %!!

end

Dim_pressuredrop(ij)=((4*cf1*L2(end)*Rho_water*(v_inner^2))/2)+(4*cf2*L2(en
d)*Rho_cutting*(v_annular^2))/2;

Dim_pump(ij)=(mflow/((Rho_water+Rho_cutting)/2))*Dim_pressuredrop(ij);

EnergyTot_cross(ij)=(sum(Energy1_cross)+sum(Energy2_cross)+sum(Energy_cutti
ngs_cross))*N ;
EnergyCross_meter(ij)=(EnergyTot_cross(ij))/(3600*1000*2138*N);

EnergyTot_meter(ij)=EnergyCross_meter(ij)+EnergyVertical_meter(ij)*2;

end

if ij >= 2
```

```
figure
plot(mflow1,EnergyTot_meter*0.0036)
title('EnergyTotmeter')
xlabel('kg/s')

figure
plot(mflow1,Dim_pump/730)
title('dimensionerande för pumpe')
xlabel('kg/s')

figure
plot(mflow1,EnergyVertical_meter)
title('Energyverticalmeter')
xlabel('kg/s')
end

disp(['Pump capacity required = ', num2str(Dim_pump),' W'])
disp(['Pump capacity required (HK) = ', num2str(Dim_pump/730),' Hk'])
disp(['Energy used per meter drilled vertical well = ',
num2str(EnergyVertical_meter),'  kWh/m'])
disp(['Energy used per meter drilled cross well = ',
num2str(EnergyCross_meter),'  kWh/m'])
disp(['Energy used per meter total = ', num2str(EnergyTot_meter),'
kWh/m'])
```

Model 2 – Mechanical energy for lifting drill string out of well

```
% Comment:
% Maximum depth =5000 m, with x=2138.

close all
clear all
clc

% Mass of the drillstring and drillhead:

m_drillcollar=149;

mhead_vertical=80;
m_vertical=m_drillcollar+mhead_vertical;

% Constants:

g = 9.81;
a = 1;
L0 = 27;
La = 8;

int = 378;
Depth = 4914;

L1=[378:int:Depth];

A=14;

L2=[L0:L0:Depth];

Weight=20000;
intervall=0;

for i=1:length(L1)

    for j=1:length(L2)

if L2(j)<=L1(i)

    L(i,j)=j*L0;
    M(i,j)=L(i,j)*m_vertical;
    Fg1(i,j)=g*M(i,j);
    Fa(i,j)=a*M(i,j);

   % Fg2(i,j)=g*M(i,j);

   % Fg3(i,j)=g*(M(i,j)-Weight);
```

```
    Pg1(i,j)=Fg1(i,j)*L0;

    Pa(i,j)=Fa(i,j)*La;

   % Pg2(i,j)=Fg2(i,j)*L0;

   % Pg3(i,j)=Fg3(i,j)*L0;

end
    end
end

plot(L1, sum(Pg1'))

sum(sum(Pg1'))
sum(Pa')
sum(Pg1')
%sum(Pg2')
%sum(Pg3')

%test = sum([1:1:Depth].*m_vertical *9.81)
figure
surf(Pg1)
ylabel('Interval 378 m')
xlabel('Interval 27 m')

% Crosswell calculation:

x=2138;

Length_cross=Depth+x;

L1_cross=[Depth:int:Length_cross]

L2_cross=[Depth:L0:Length_cross];

mhead_cross=50;

m_cross=m_drillcollar+mhead_cross;

for i=1:length(L1_cross)

  for j=1:length(L2_cross)

  if L2_cross(j)<=L1_cross(i)

    L_cross(i,j)=Depth+(j*L0);

    M_cross(i,j)=L_cross(i,j)*m_cross;

    Fg1_cross(i,j)=g*M_cross(i,j);
```

```
        Fa_cross(i,j)=a*M_cross(i,j);

        %Fg2_cross(i,j)=g*M_cross(i,j);

        %Fg3_cross(i,j)=g*(M_cross(i,j)-Weight);

        Pg1_cross(i,j)=Fg1_cross(i,j)*L0;

        Pa_cross(i,j)=Fa_cross(i,j)*La;

       % Pg2_cross(i,j)=Fg2_cross(i,j)*L0;

       % Pg3_cross(i,j)=Fg3_cross(i,j)*L0;

    end

        end
end

N=21;

Q_vertical=(sum(sum(Pg1))+ sum(sum(Pa)))*2

Q_cross=(sum(sum(Pg1_cross))+ sum(sum(Pa_cross)))*N

Q_vertical_meter=Q_vertical/(3600*(10^3)*Depth*2)

Q_cross_meter=Q_cross/(3600*(10^3)*x*N)

Qtot = (Q_vertical+Q_cross)/(3600*10^3)

Qtot_meter=Qtot/((x*N)+Depth*2)

disp(['Energy used for lifting, holding and drilling per meter
= ', num2str(Qtot_meter),' kWh/m'])

disp(['Energy used for vertical wells per meter = ',
num2str(Q_vertical_meter),' kWh/m'])

disp(['Energy used for cross wells per meter = ',
num2str(Q_cross_meter),' kWh/m'])
```

Appendix E - Input to calculation models

Table 9.1 – Input to mechanical energy

Input	Value	Unit	Source
Size drill collar	6 ½	inch	A. Rødland
Mass drill collar	149	kg/m	http://www.drill-pipes.com/drill-collars.php
Mass drill head 12 1/4"	80	kg	E. Normann
Mass drill head 8,5"	50	kg	E. Normann
Weight on bit	20000	kg	E. Normann
Interval for assembly /disassembly of stand	27	m	T. Gjersvik
Maximum velocity when lifting drill string	4	m/s	T. Gjersvik
Acceleration	1	m/s2	Assumption
Lifetime drill head	500	m	T. Gjersvik
Distance drilled before each elevation to the surface	378	m	T. Gjersvik

Table 9.2 – Input to pump calculation

Input	Value	Unit	Source
Mass flow drilling mud	42	kg/s	A. Rødland
Diameter drill collar	6 ½	inch	A. Rødland
Diameter annulus	Same as drill head	inch	A. Rødland
Relative roughness on wall	0,002	NA	Rock Energy (Geocalc)
Effective rate of penetration	10	m/s	E. Normann
Interval assembly/disassembly of drill string	27	m	T. Gjersvik

Table 9.3 – Calculation of materials for drill heads

	Entry	Value	Unit	Comment
Mass	Drill head 12 1/4''	80	kg	
	Drill head 8 1/2''	50	kg	
Composition	2/3 volume % boron carbid			
	1/3 volume % Copper manganese			
Density	Boron Carbide	3300	kg/m3	Based on 86% Cu,
	Copper Manganese	8715	kg/m3	14% Mn
Mass composition	50 kg drill head (8,5'') mass composition	28,45	kg CuMn	
		21,55	kg Boron carbide	
	80 kg drill head (12,25'') mass composition	45,52	kg CuMn	
		34,48	kg Boron carbide	
	No of drill heads 12,5 ''	19,25	pcs.	Based on 500 m
	No of drill heads 8,5 ''	89,8	pcs.	lifetime
	Total mass CuMn	3431	kg	
	Total mass Boron carbide	2599	kg	
Without cross well design	80 kg drill head (12,25")	876,3	kg CuMn	14 % Mn, 86% Cu
		663,7	kg Boron carbide	

Appendix F - Results of background processes' contribution to the results

Scenario 1 –Norwegian electricity mix:

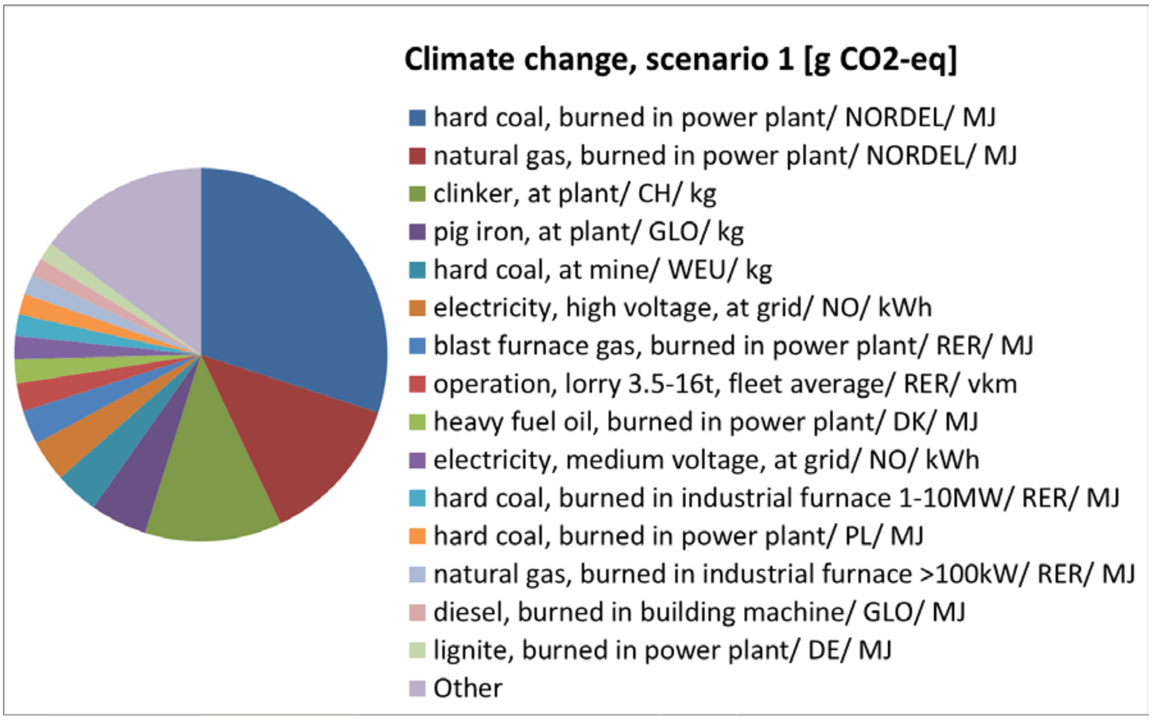


Figure 9.2 – Climate change, scenario 1, Norwegian electricity mix

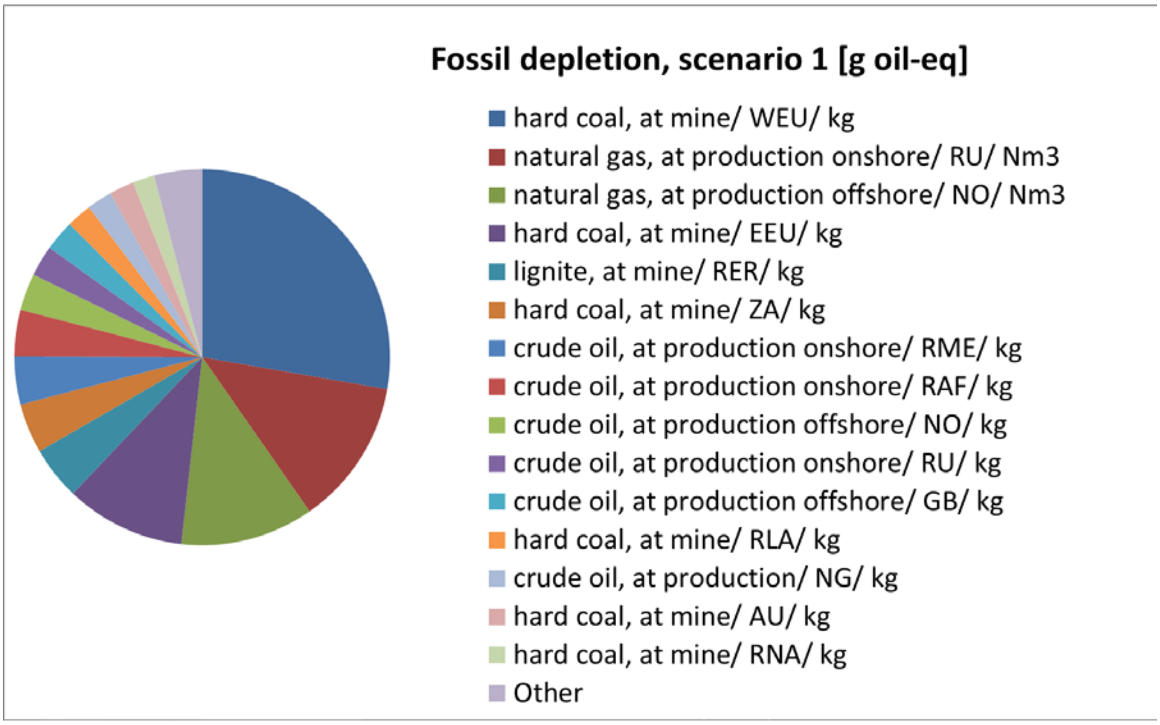


Figure 9.3 – Fossil depletion, scenario 1, Norwegian electricity mix

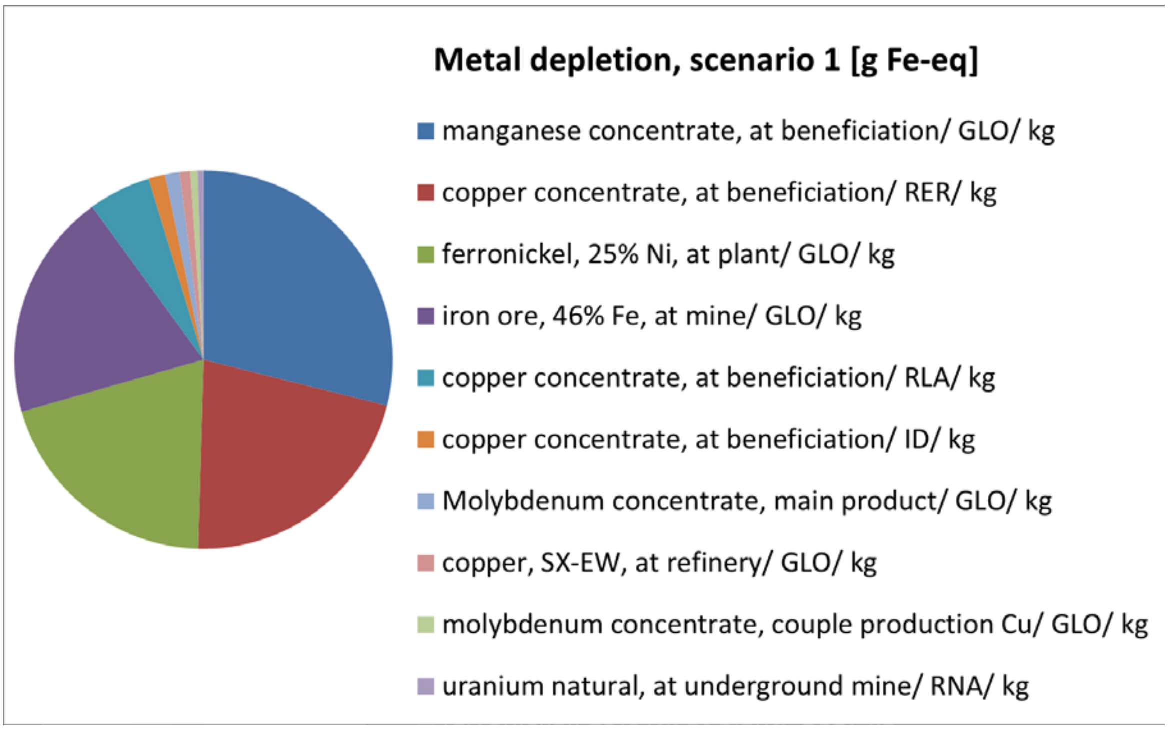


Figure 9.4 – Metal depletion, scenario 1, Norwegian electricity mix

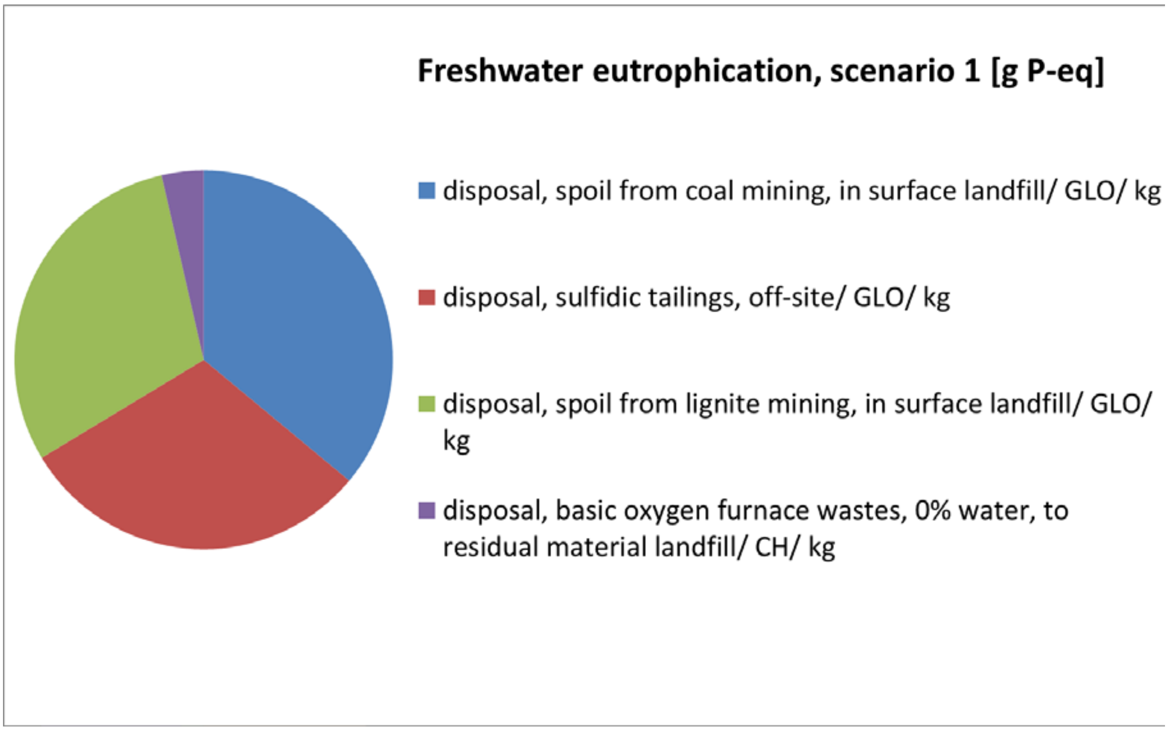


Figure 9.5 – Freshwater eutrophication, scenario 1, Norwegian electricity mix

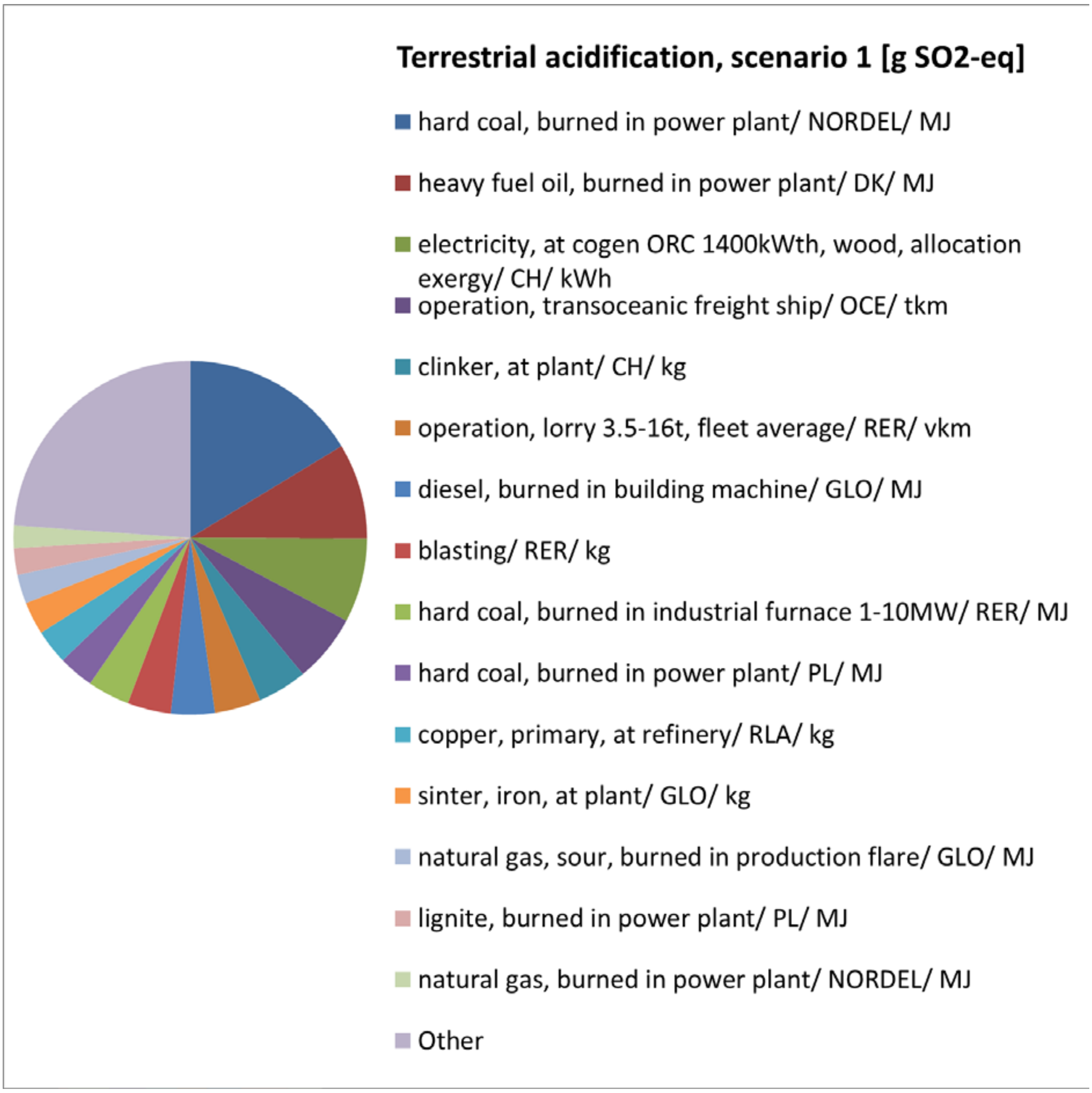


Figure 9.6 – Terrestrial acidification, scenario 1, Norwegian electricity mix

Scenario 1 –Diesel

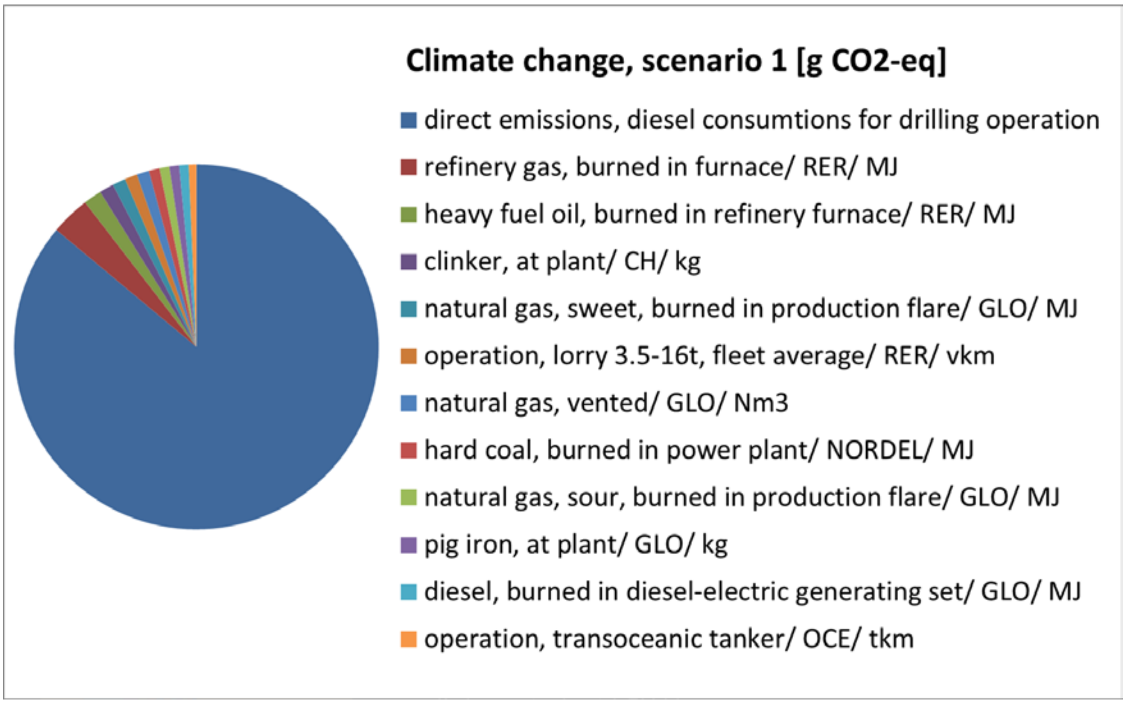


Figure 9.7 – Climate change, scenario 1, Diesel

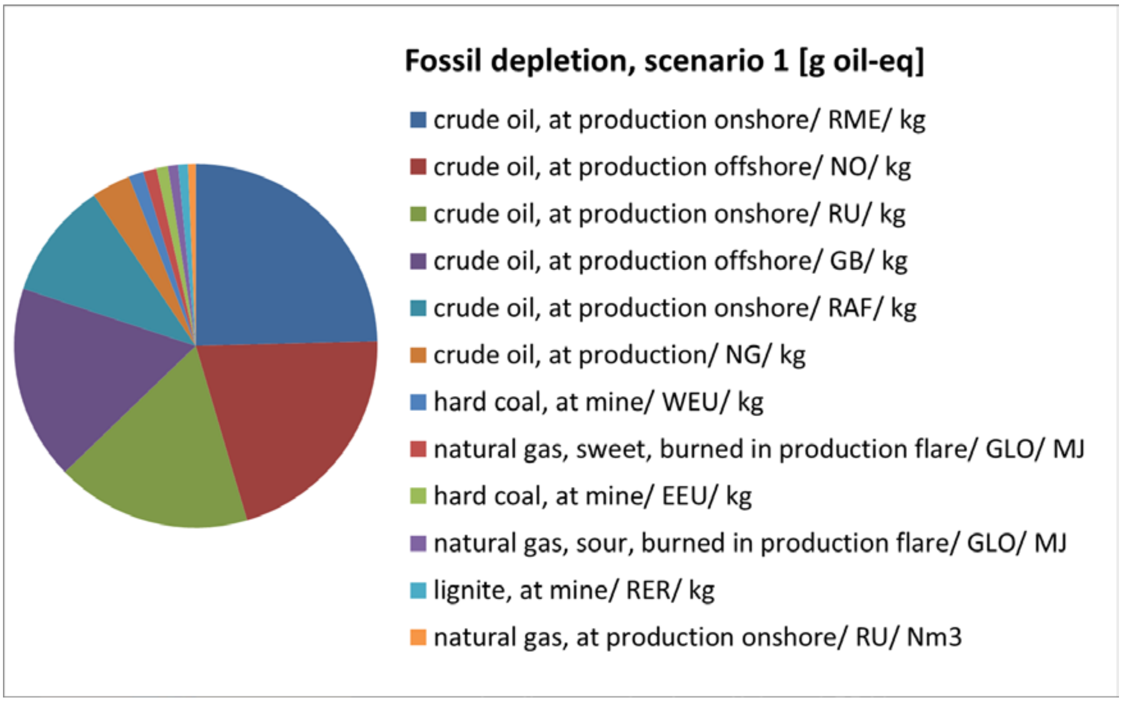


Figure 9.8 – Fossil depletion, scenario 1, Diesel

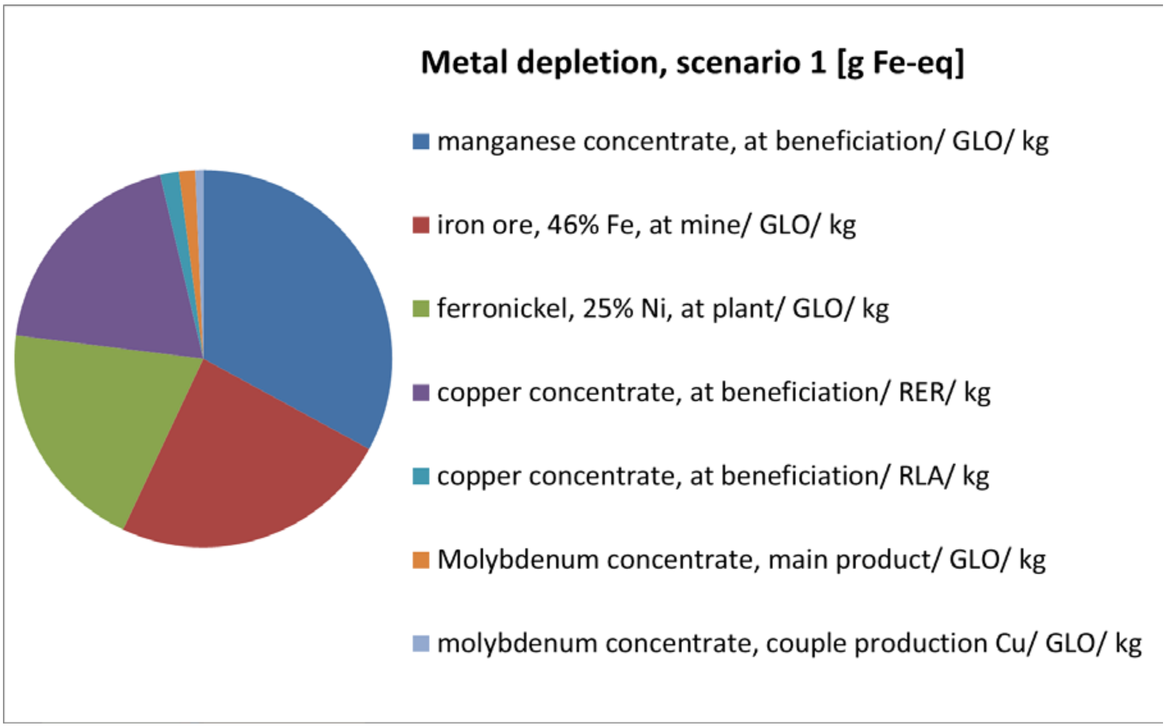


Figure 9.9 – Metal depletion, scenario 1, Diesel

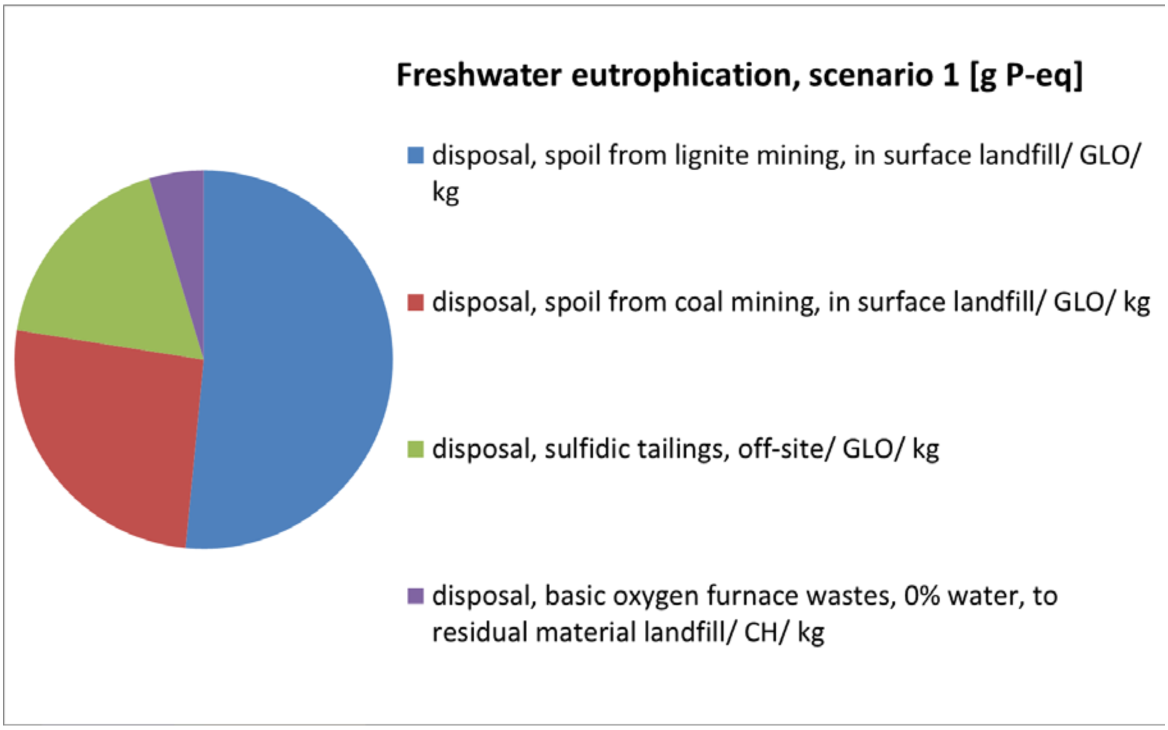


Figure 9.10 – Freshwater eutrophication, scenario 1, Diesel

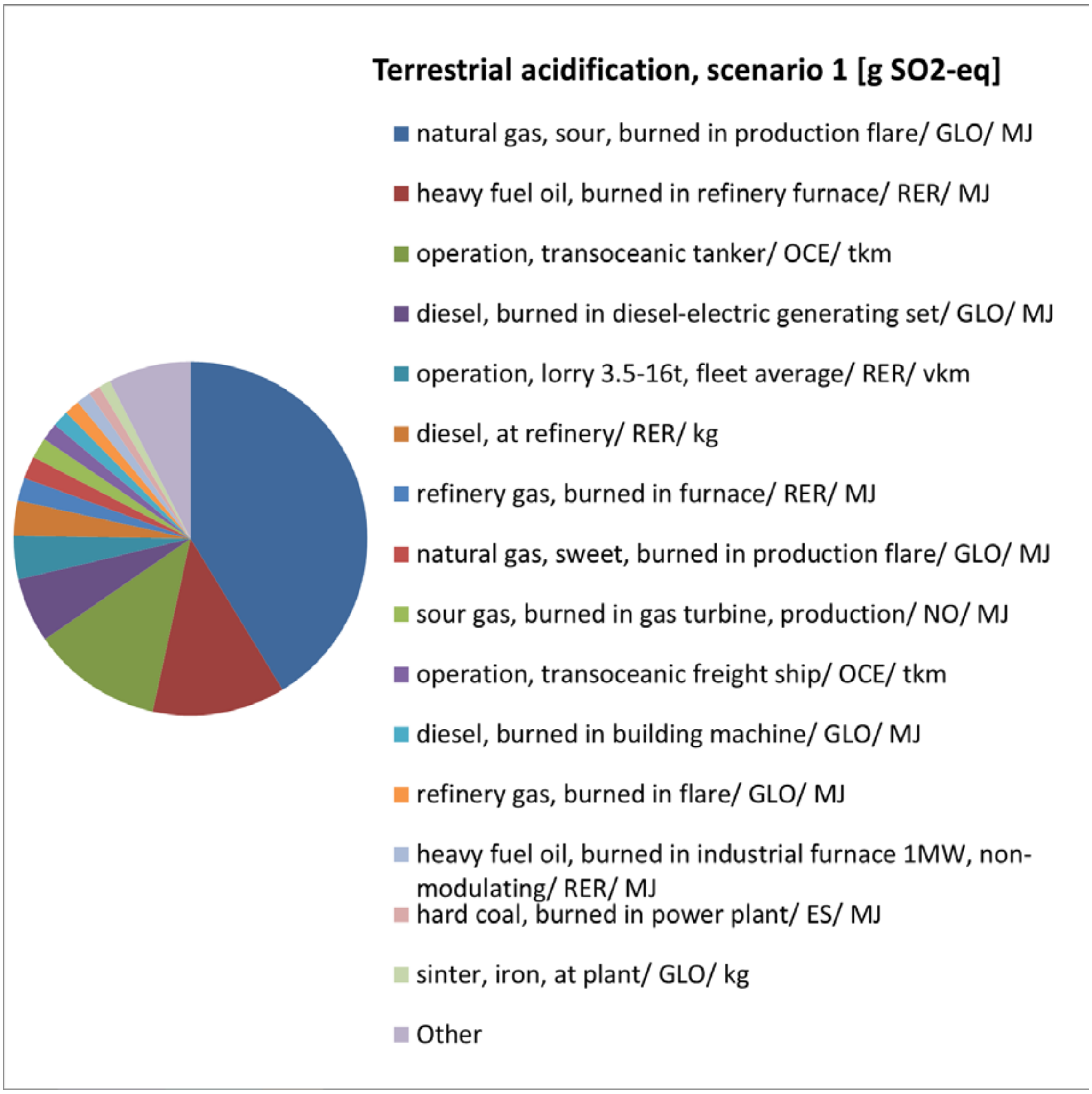


Figure 9.11 – Terrestrial acidification, scenario 1, Diesel

Scenario 1 –European electricity mix

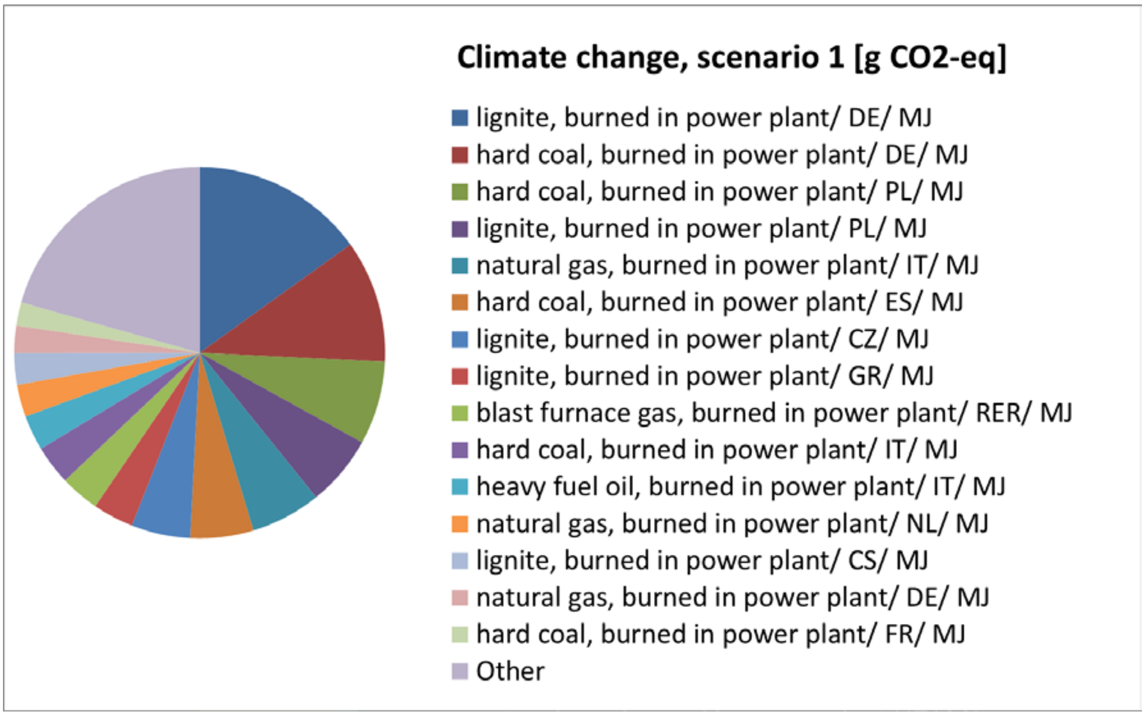


Figure 9.12 – Climate change, scenario 1, European electricity mix

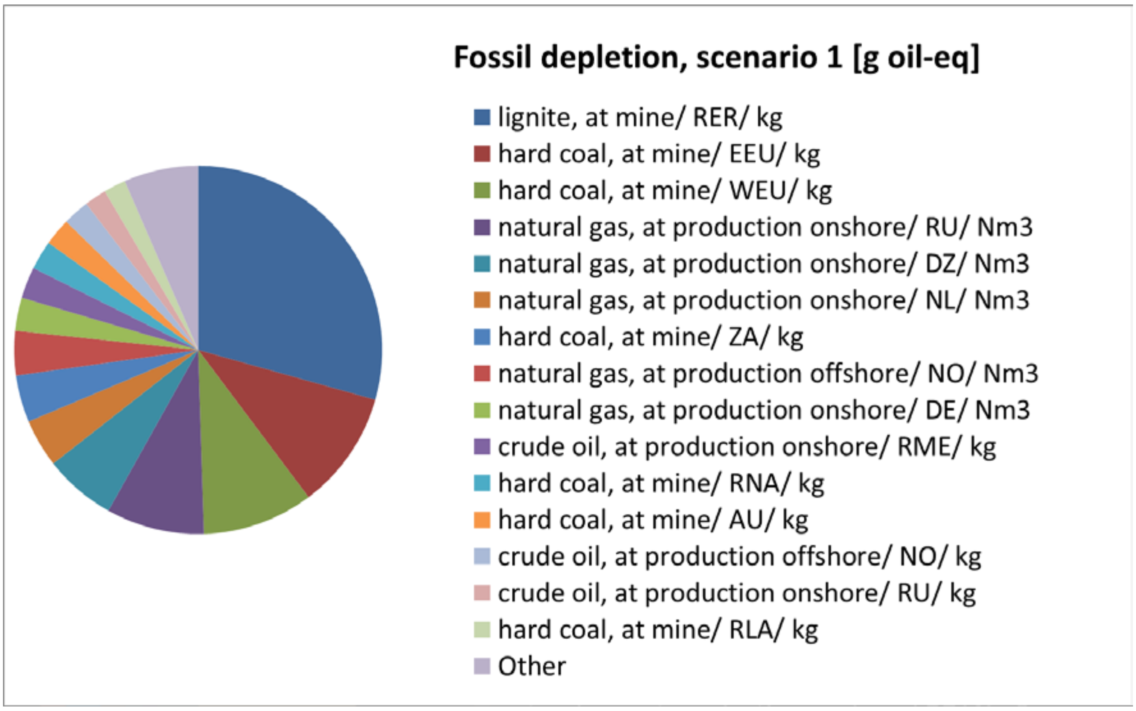


Figure 9.13 – Fossil depletion, scenario 1, European electricity mix

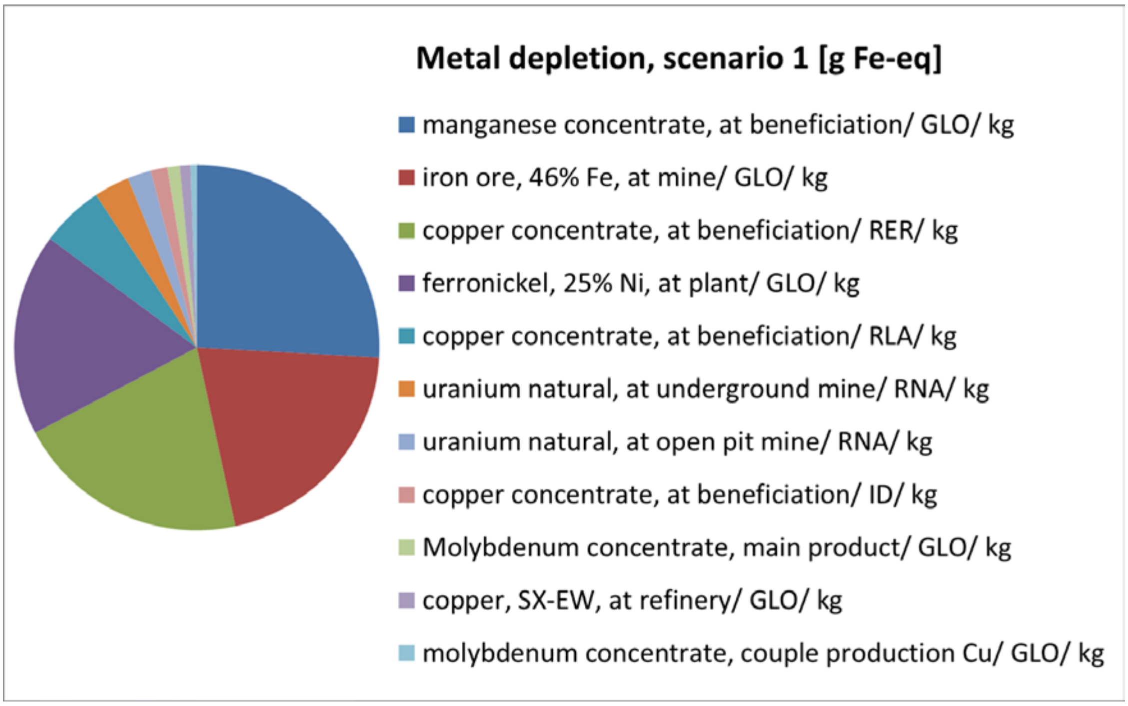


Figure 9.14 – Metal depletion, scenario 1,European electricity mix

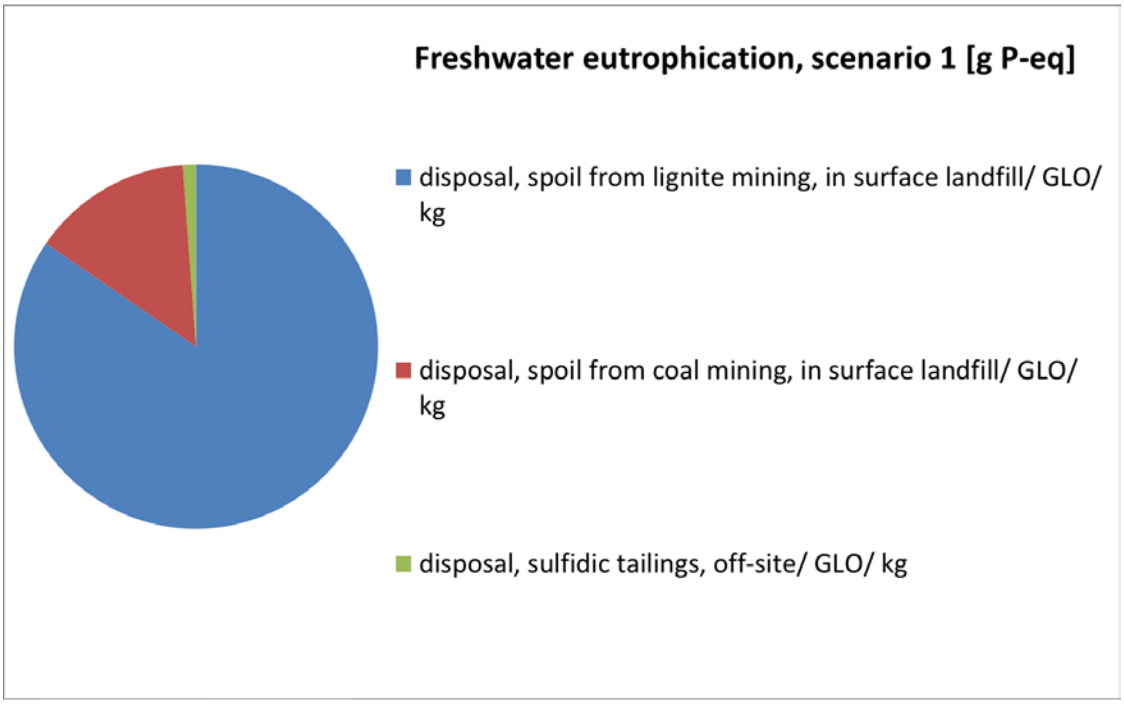


Figure 9.15 – Freshwater eutrophication, scenario 1, European electricity mix

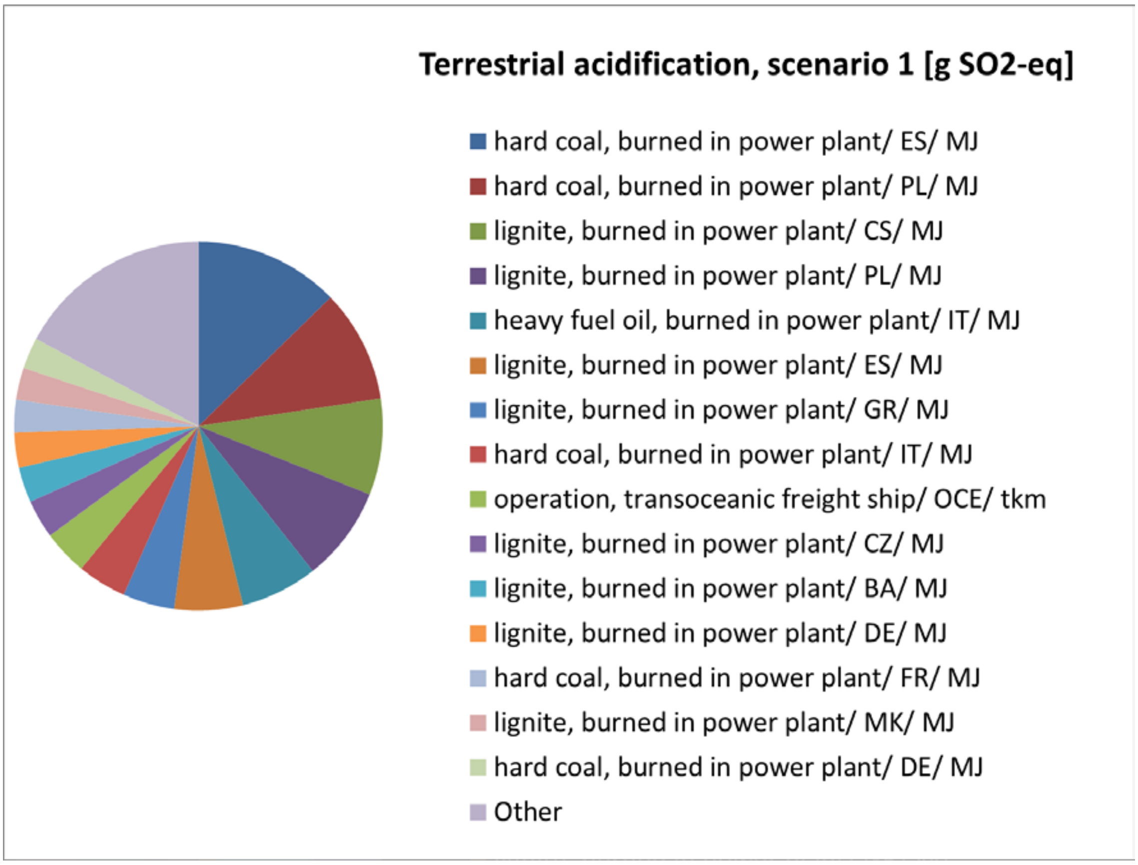


Figure 9.16 - Terrestrial acidification, scenario 1, European electricity mix

Scenario 2 –Norwegian electricity mix:

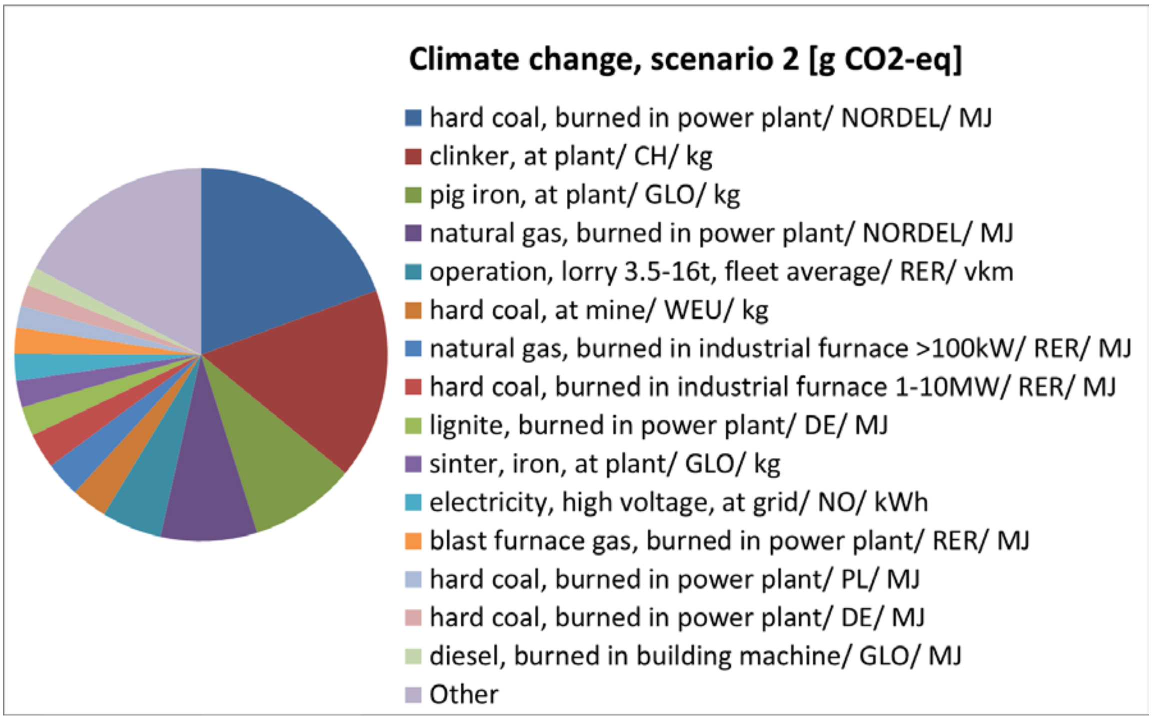


Figure 9.17 – Climate change, scenario 2, Norwegian electricity mix

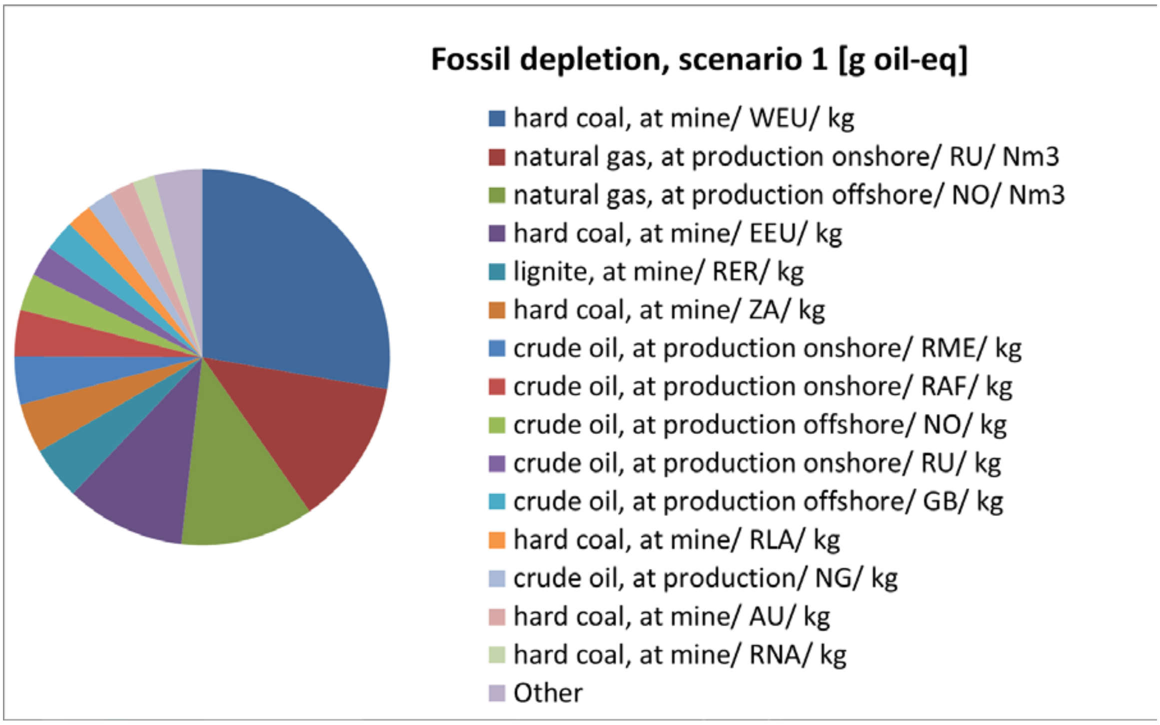


Figure 9.18 – Fossil depletion, scenario 2, Norwegian electricity mix

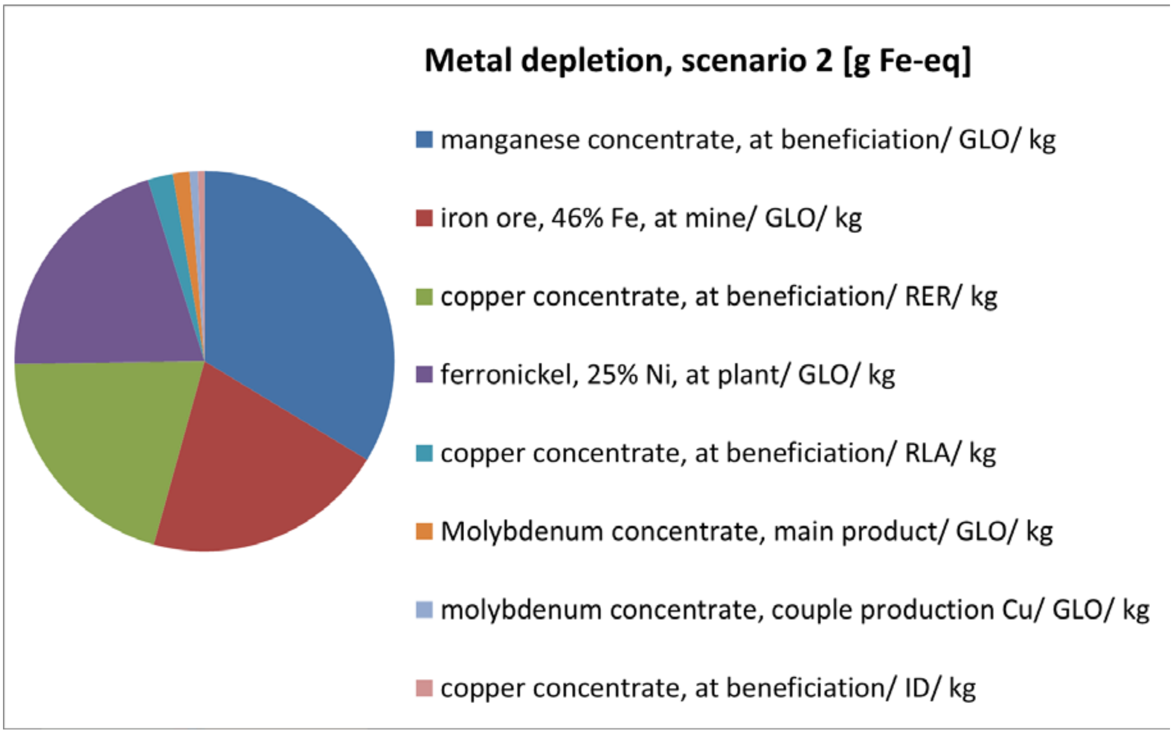


Figure 9.19 – Metal depletion, scenario 2, Norwegian electricity mix

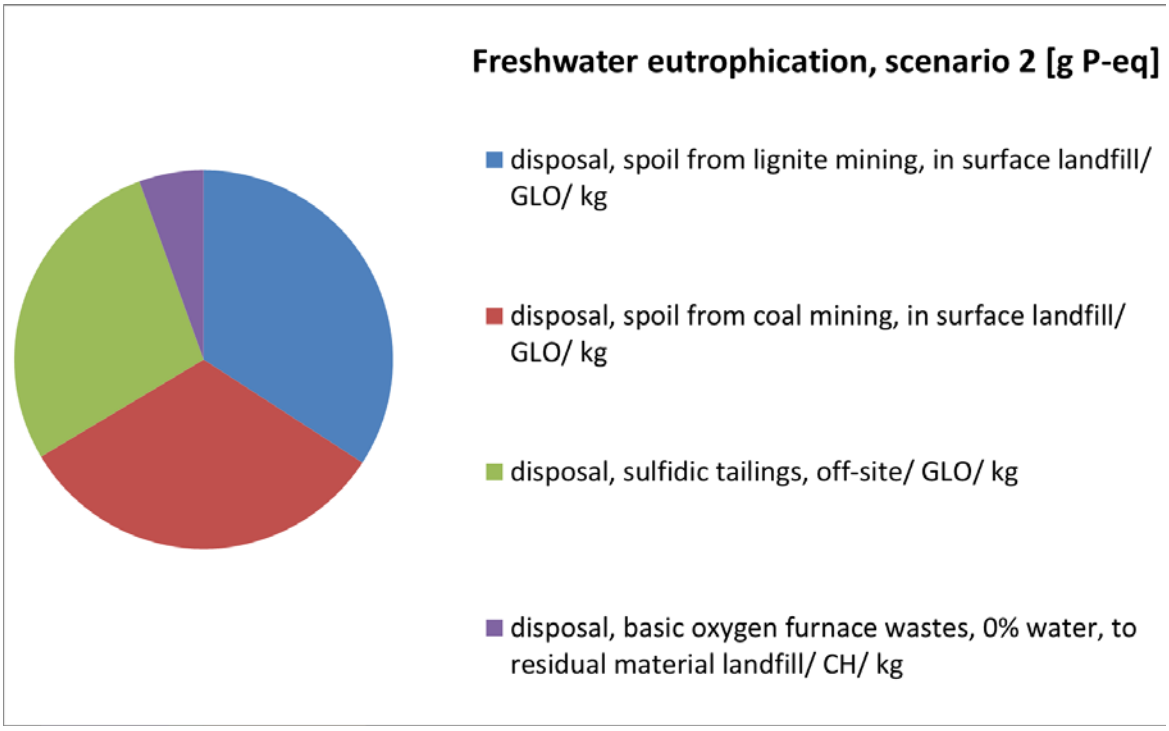


Figure 9.20 – Freshwater eutrophication, scenario 2, Norwegian electricity mix

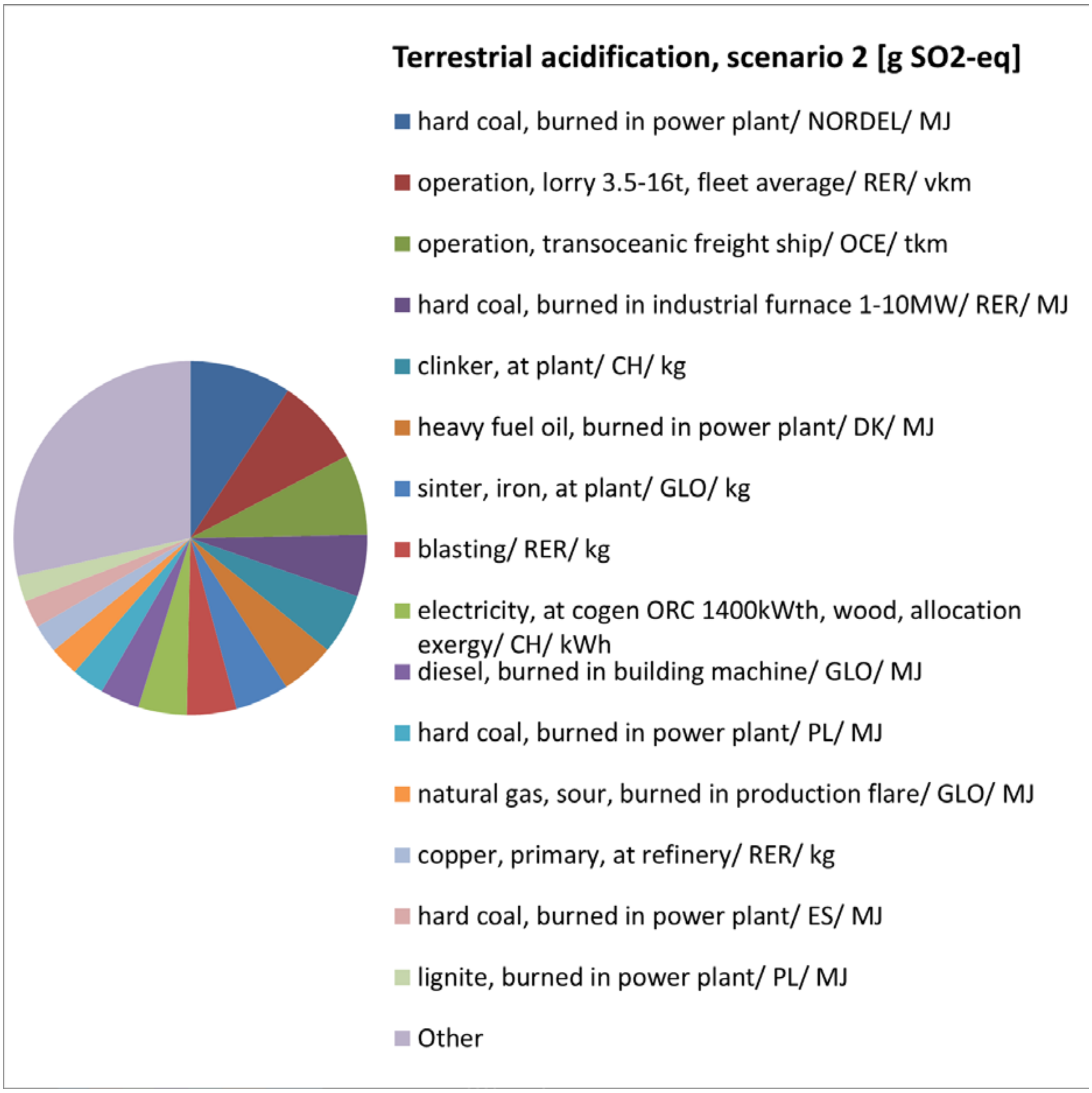


Figure 9.21 - Terrestrial acidification, scenario 2, Norwegian electricity mix

Scenario 2 –Diesel

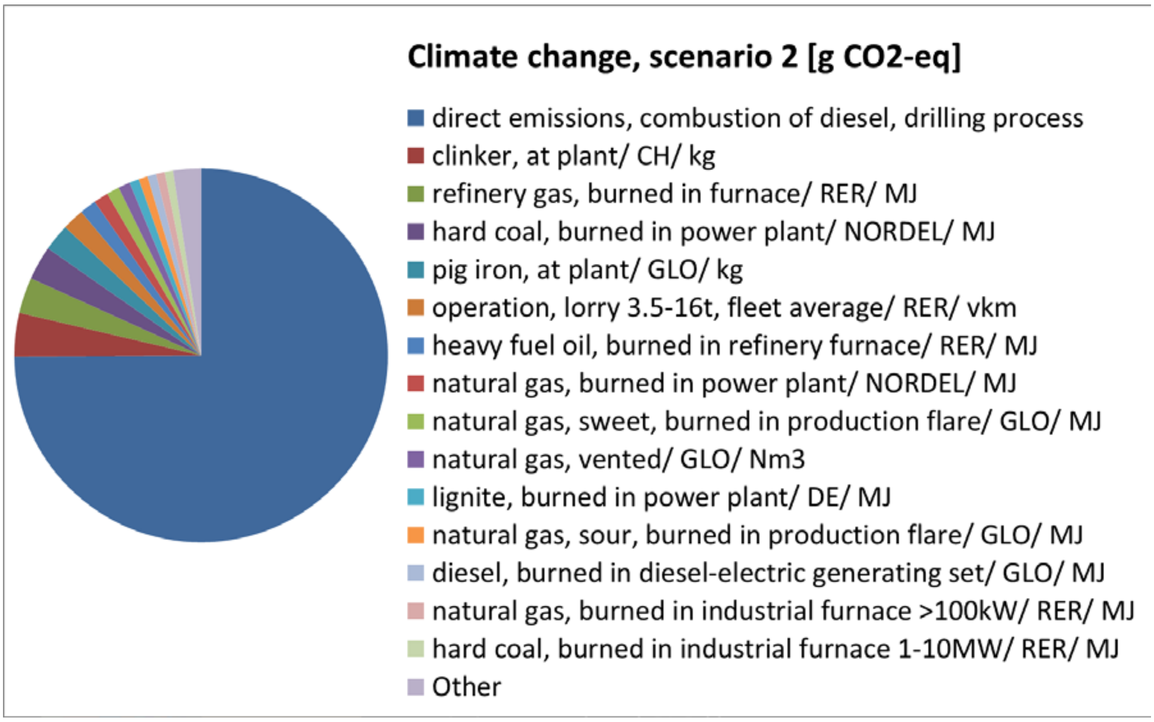


Figure 9.22 – Climate change, scenario 2, Diesel

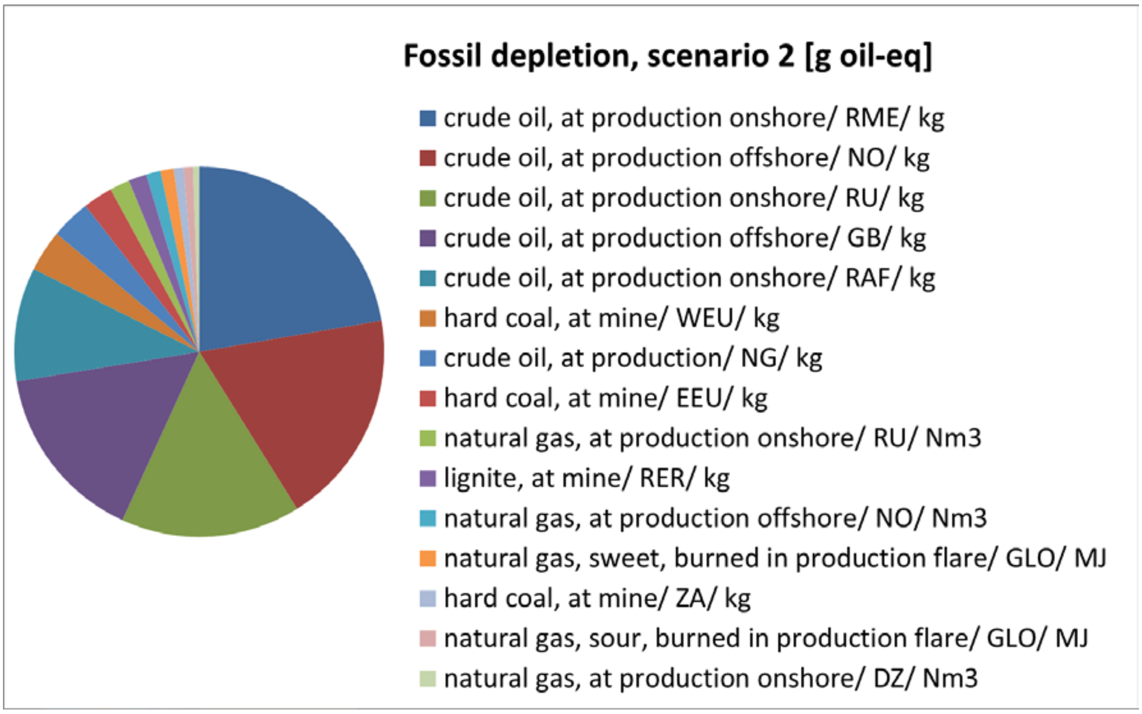


Figure 9.23 – Fossil depletion, scenario 2, Diesel

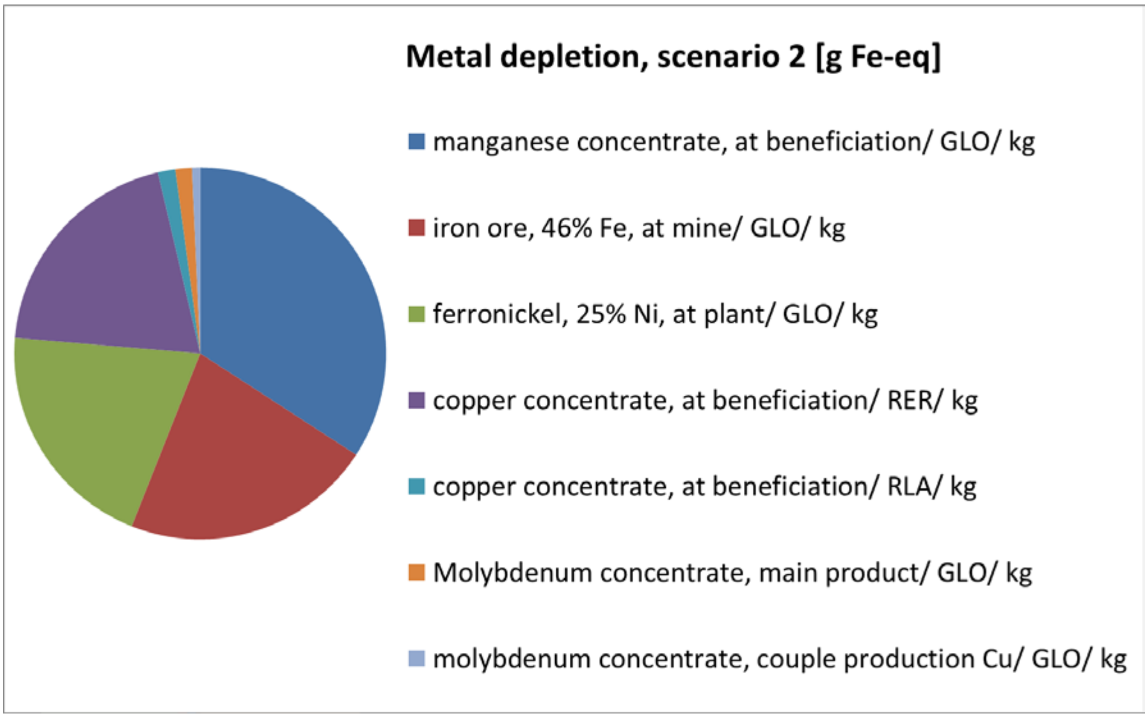


Figure 9.24 – Metal depletion, scenario 2, Diesel

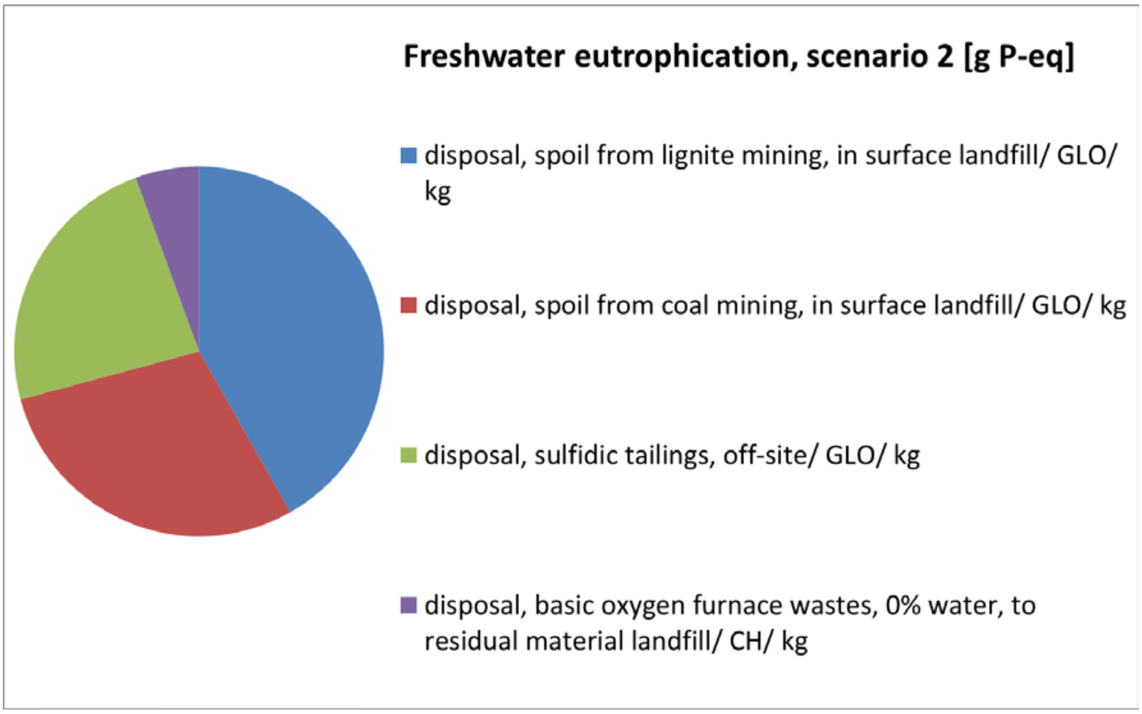


Figure 9.25 - Freshwater eutrophication, scenario 2, Diesel

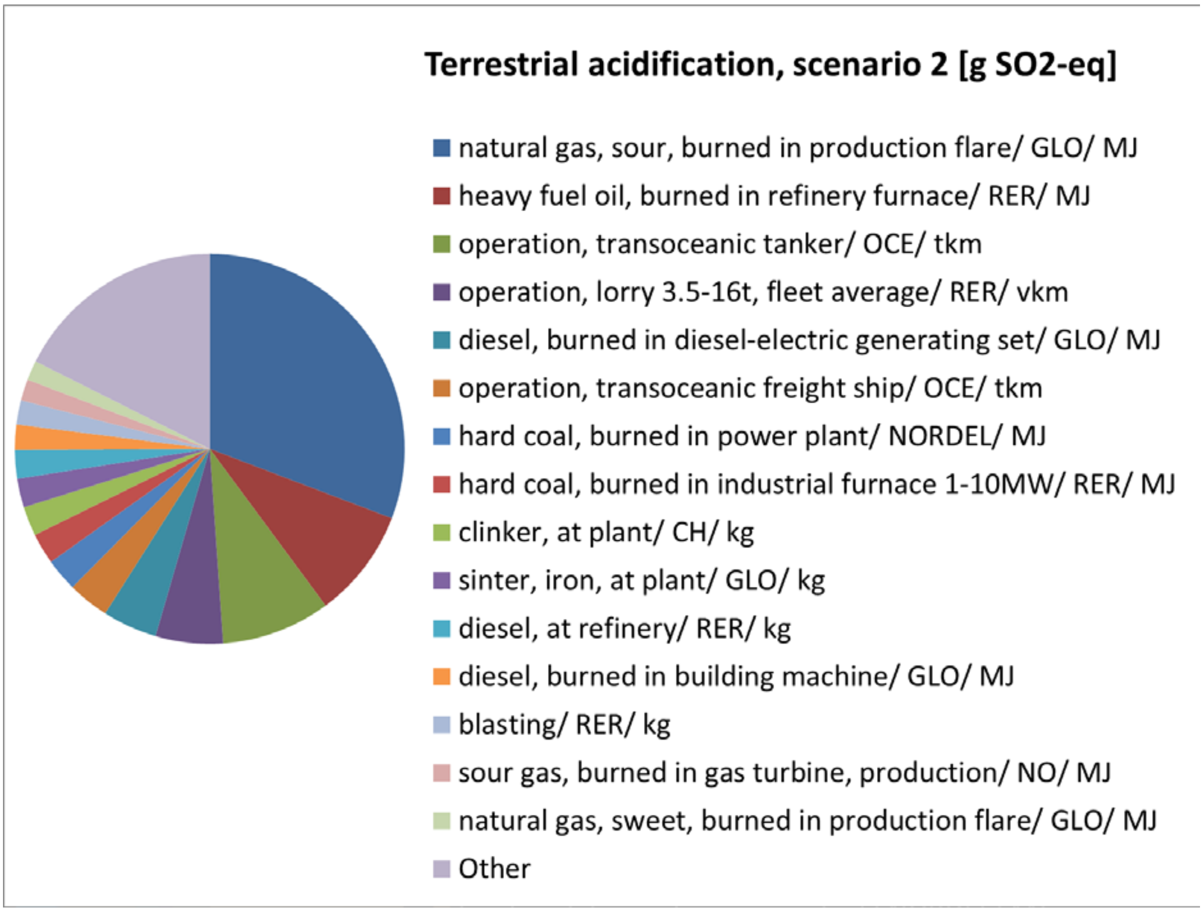


Figure 9.26 – Terrestrial acidification, scenario 2, Diesel

Scenario 2 –European electricity mix

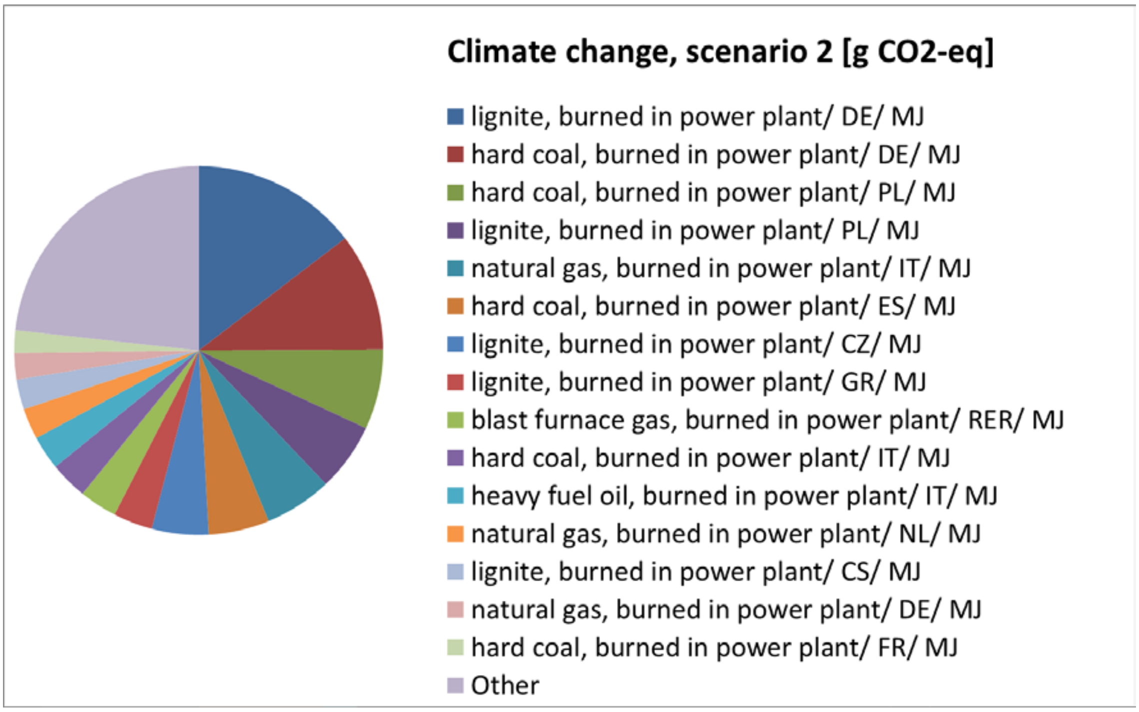


Figure 9.27 – Climate change, scenario 2, European electricity mix

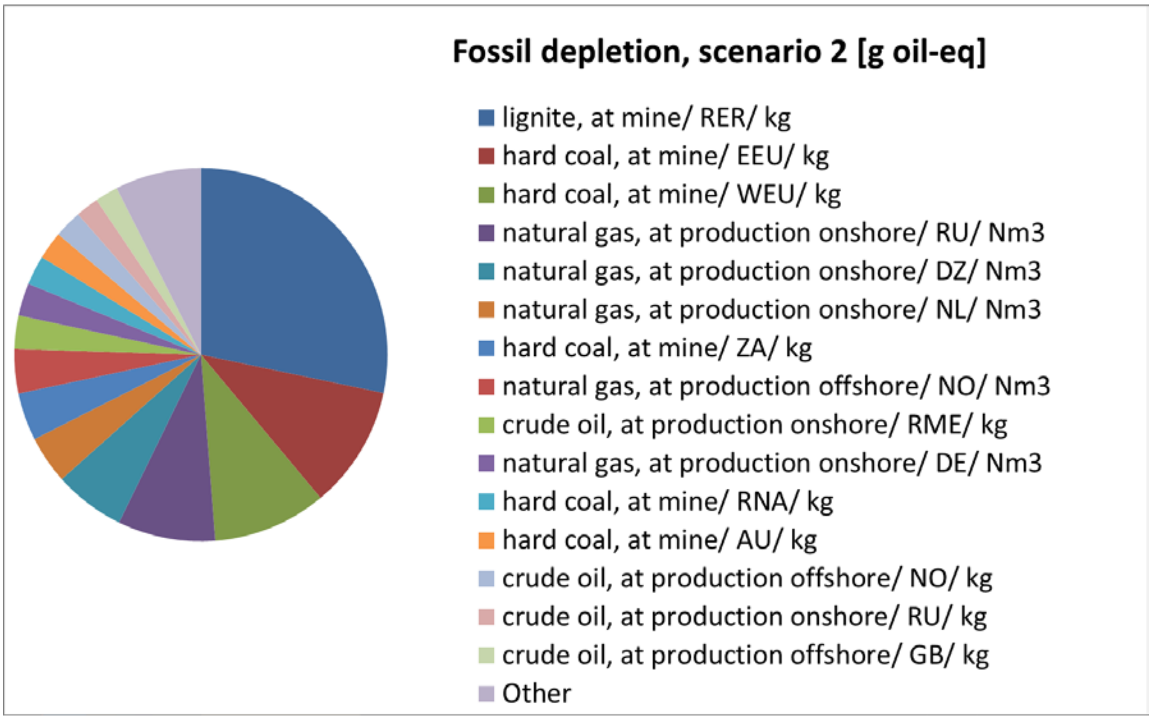


Figure 9.28 – Fossil depletion, scenario 2, European electricity mix

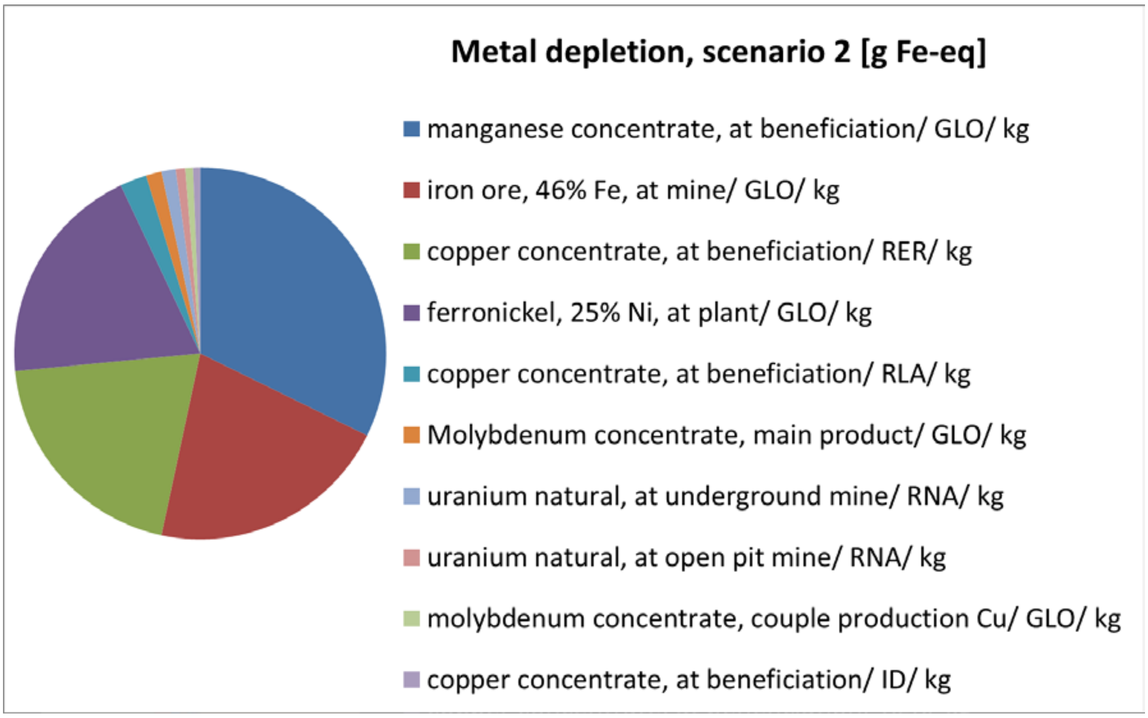


Figure 9.29 – Metal depletion, scenario 2, European electricity mix

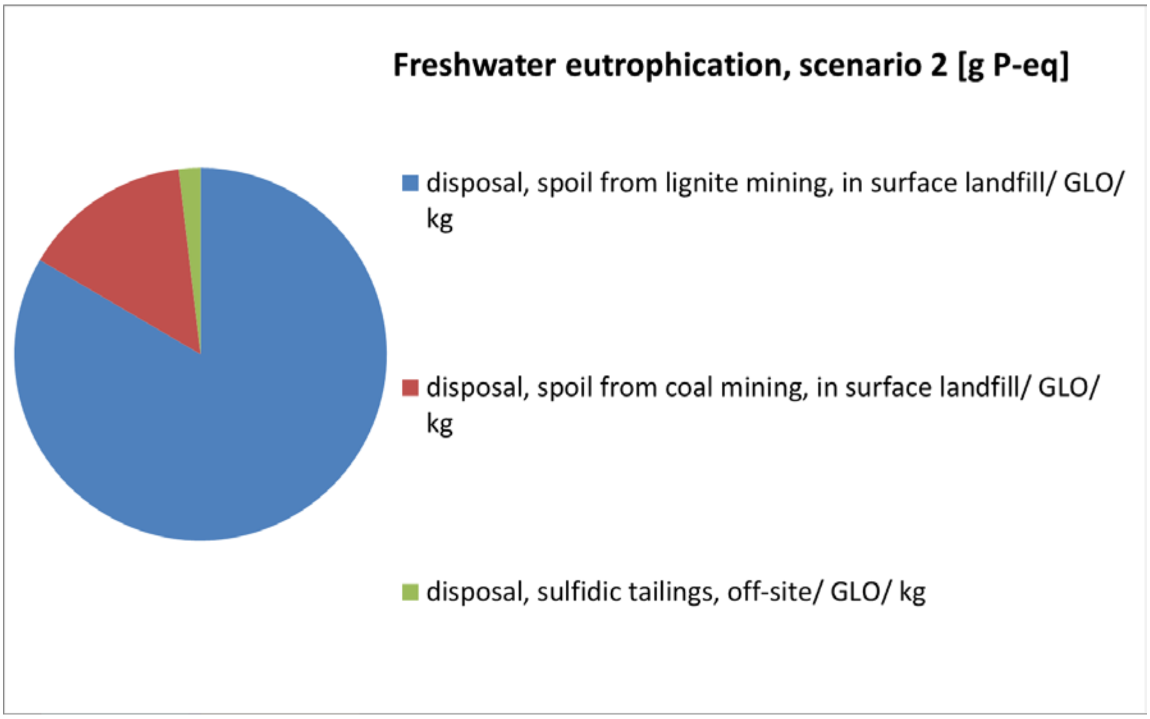


Figure 9.30 – Freshwater eutrophication, scenario 2, European electricity mix

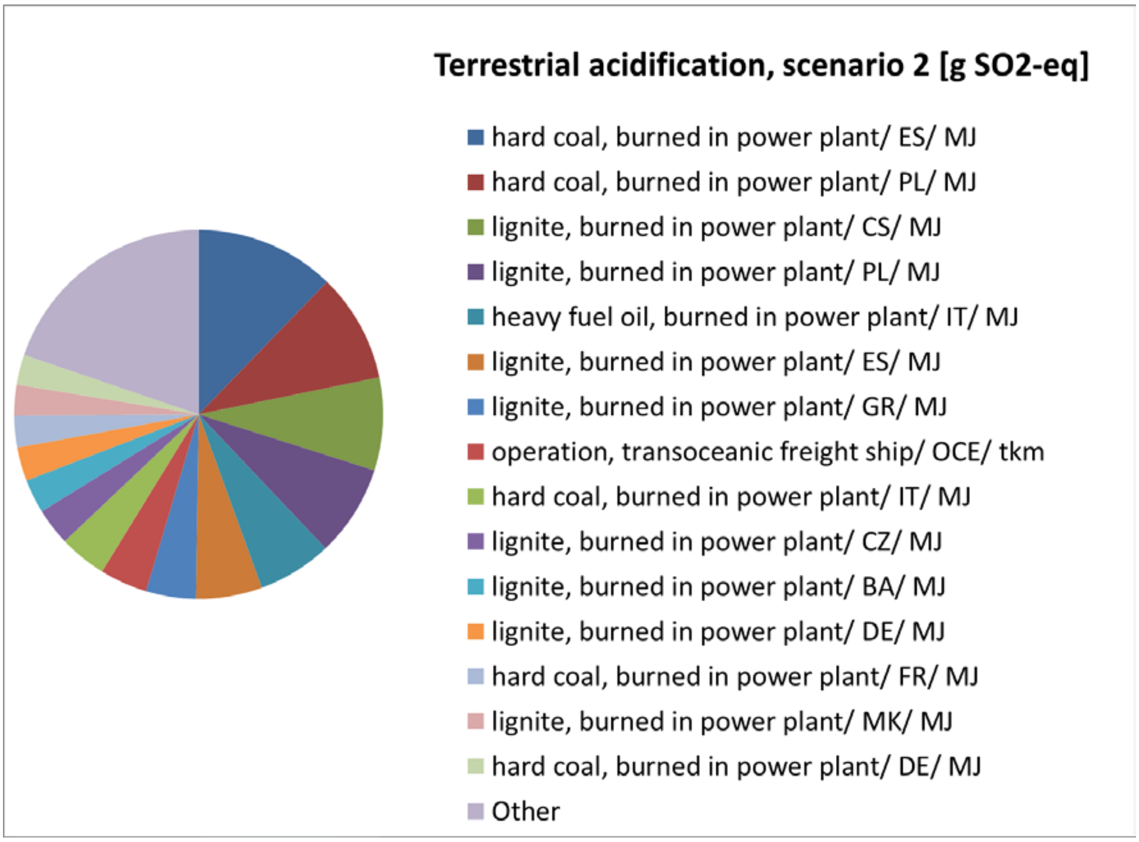


Figure 9.31 - Terrestrial acidification, scenario 2, European electricity mix