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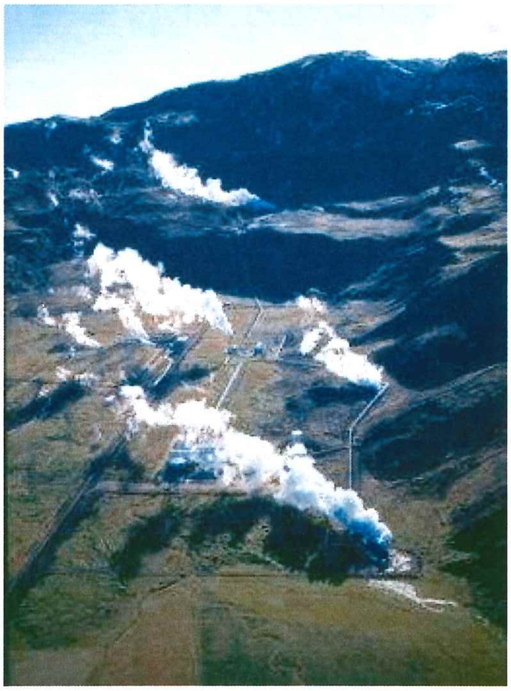

Nesjavellir geothermal plant

Life cycle analysis of Nesjavellir geothermal power plant

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Summary

This report includes the results from a project carried out by IceTec (Iðntæknistofnun) in cooperation with Orkuveita Reykjavikur, Landsvirkjun and Hitaveita Suðurnesja. The project was funded by the Icelandic energy fund (Orkusjóður) and the project participants. The aim of this project was to examine the environmental impact of the production of 1kWh of produced energy from a geothermal power-plant in Iceland. The method used to analyse the environmental impact was Life Cycle Analysis.

A specific geothermal power plant, Nesjavellir power plant, was the reference power plant in this study. Nesjavellir is so called co-generating power plant, producing both electrical energy and thermal energy. This analysis considers the environmental impact of the electrical production and also the environmental impact of the co-generation. The functional unit of this study was 1kWh of energy produced and the reference year was the operational year 2002.

The main results from the analysis are that two of the gases, hydrogen sulphide and carbon dioxide, that are released from the geothermal steam during the operational phase are the largest contributors to the overall environmental effects. Hydrogen sulphide (H_2S) is a gas that contributes to acid rain (acidification) when converted into sulphur dioxide (SO_2). Carbon dioxide (CO_2) is a gas that contributes to global warming. The emissions of hydrogen sulphide are according to the eco-points distribution a greater environmental threat than the emissions of the carbon dioxide. These results are tentative, since the conversion of hydrogen sulphide to sulphur dioxide in Iceland may be less than 100% which is the conversion rate used in the eco-indicator. In studies performed by Kristmannsdottir et al. (2003) the conversion rate of hydrogen sulphide to sulphur dioxide was far from a 100%. This stresses the importance of further studies in the field of the fate of the hydrogen sulphide emissions in Iceland. Also, there are natural changes in the concentration of these gases that influence the results.

The release of greenhouse gases due to the production of metals for the construction of the power plant is the second largest contributor to the environmental effects. That is after the emissions in the geothermal steam. The metals in the hot water transport pipe to Reykjavik have the largest impact, when looking at the co-generating production. The results from the construction phase also show that the power house with the turbines and generators is a large contributor to the environmental impacts in this phase. From the main results of the analysis it is clear that there is a great environmental benefit of utilizing the thermal energy from the electricity production for district heating purposes. This is clear when looking at emissions per kWh of the co-generating production compared to only the electrical production in Figures 9 and 10.

Compared to fossil energy production systems, emissions of greenhouse gases from Nesjavellir power plant are low but sulphur emissions are slightly higher.

Improvements could be to clean out the hydrogen sulphide and the carbon dioxide. Capture it from the steam for permanent storage or other disposal. Other improvements could be to use metals with a good environmental profile and recycle as much as possible.

Table of content

1 Introduction

This report contains the results and methodology of a life cycle analysis (LCA) of Nesjavellir geothermal power plant in Iceland. The report is the results of a project funded by the Icelandic energy fund, Orkusjóður, IceTec (Iðntæknistofnun), Orkuveita Reykjavikur, Hitaveita Suðurnesja and the National power company of Iceland, Landsvirkjun. The goal of the project was to make an analysis of the total environmental impacts of electrical power generation from geothermal energy resources in Iceland. It was decided to take a specific case; the geothermal power plant at Nesjavellir. Nesjavellir is a co-generating power plant, i.e. a power plant producing both electrical and thermal energy. Nesjavellir power plant is operated by Orkuveita Reykjavíkur. The project dealt separately with both environmental impacts of only the electrical power production and the production of the thermal energy.

The project leaders would like to thank the following persons for their important contribution and cooperation: Einar Gunnlaugsson, Orkuveita Reykjavíkur, Gestur Gíslason, Orkuveita Reykjavíkur, Ragnheiður Ólafsdóttir, Landsvirkjun, Ellen Mälender, former M.Sc.student at the University of Stuttgart and Arngrímur Thorlacius, IceTec.

The overall management and detail enquiries of the data collection were performed by Thorhildur Kristjansdottir, Steinar Beck Baldursson and Halla Jonsdottir at IceTec. Data on material use for the construction phase was mostly gathered by Edda Sif Aradottir, Orkuveita Reykjavikur in the summer 2003, and material and energy use for the utilization phase was mainly gathered from Gestur Gislason and Einar Gunnlaugsson at Orkuveita Reykjavikur. The data analysis program used was Gabi4 from Germany. Not all data were available, therefore some estimations and simplifications were made; this is discussed further in Section 6.6.

The purpose of the study was to acquire knowledge of key environmental impact processes of utilization of geothermal energy. Knowledge of the important environmental effects of utilization of geothermal energy is important for decision makers in the energy sector and for the authorities in Iceland. This can help to make the utilization of the Icelandic geothermal energy sources with as small environmental effects as possible.

The structure of the report is as follows: In Section 2, a general insight into the utilization of geothermal energy is given with an overview of the Icelandic geothermal circumstances. Further in Section 3, there is a short introduction to life cycle analysis. In Section 4, there is a short overview of the general environmental effects from the production of energy from geothermal resources. In Section 5, Nesjavellir power plant is introduced with historical and technical information. The structure and inventory information is given in Section 6. The impact assessment and results of the analysis is in Section 7. Section 8 contains discussions and conclusions.

2 Geothermal energy

Geothermal energy is the thermal energy in the earth's interior. It can be defined as the heat transferred from the earth's interior, which has very high temperatures of 5000 – 6000 C°, to rocks or water located relatively close to the earth's surface. The geothermal gradient is an expression of the increase in temperature with depth into the earths crust. The average geothermal gradient is about 2.5-3 °C/100 m (Dickson, et. al., 2004)

Geothermal energy can be utilized either directly for heating (hot water), drying, bathing, district heating or to produce electricity with geothermal steam.

In Iceland geothermal fields are defined as either low temperature or high temperature. The general definition of a low temperature area is that its temperature is less than 150°C at a depth of about 1000 m. High temperature areas are only found on active volcano belts or along their periphery. The water temperature in high temperature areas should be no lower than 200°C at a depth of 1000m. (Orkuveita Reykjavíkur, 2004)

Of the total world energy production, geothermal energy only amounts to around 0.0023 %, which is only a fraction of the global geothermal power potential. In the year 2000, geothermal resources have been identified in over 80 countries (Fridleifsson, 2001). Figure 1 shows a map of the world with locations of abundant geothermal energy resources.

Figure 1. Locations of abundant geothermal energy resources (www.power-technology.com).

2.1 *Icelandic geothermal fields*

Iceland lies on the Mid Atlantic Ridge, a fracture zone that forms an underwater mountain range and a rift, splitting the earth's crust under the Atlantic Ocean from north to south. (Orkuveita Reykjavíkur, 2003). The ridge goes through the centre of Iceland and therefore the country has considerable geothermal energy sources. There are about 250 low temperature areas and 20-30 high temperature areas in Iceland. (Orkuveita Reykjavíkur, 2004) The energy harnessed from high temperature fields in excess of the needs for house heating will mainly be used for electric power production, like in the remote Krafla field. The first geothermal power plant, Bjarnaflag, started in 1969 in Namafjall in the North East of Iceland. Bjarnaflag still has the capacity of 3 MW. Geothermal energy fulfils around 65% of the primary energy consumption in Iceland and amounted to 110.000 TJ in 2006 (Orkustofnun, 2007). The electricity production from geothermal power plants is about 2630 GWh per year, which is about 26,5% of the total electric energy production in Iceland (Orkustofnun, 2007).

In 2006 there were 7 geothermal fields utilized for electricity production:

- Nesjavellir 120 MW
- Svartsengi 46,5 MW
- Reykjanes 100 MW
- Bjarnarflag (Námafjall) 3 MW
- Krafla 60 MW
- Húsavík power plant 2 MW
- Hellisheiði 90 MW (will be expanded to 280 MW)

In 2006 several plans were being made for increasing the geothermal utilization and a new power plant was started The new power plant at Hellisheiði near Reykjavik that started in September 2006 was the first phase of a 280 MW power plant by Orkuveita Reykjavikur. Landsvirkjun is planning to build a 90 MW power plant at Bjarnarflag in North East Iceland. In Iceland almost 90% of the houses are heated with geothermal hot water (Orkustofnun og Iðnaðarráðuneytið, 2006). There are hundreds of wells that have been drilled in several areas to fulfil the need of hot water usage. Hot water for district heating is found in both low and high temperature areas. Note that the Nesjavellir power plant has now an installed electrical effect of 120MW, but this analysis is made for the year 2002, when the installed electrical effect was 90MW.

3 What is Life Cycle Analysis?

- Life-cycle Analysis (LCA) is a tool to evaluate the environmental consequences of products and systems
- LCA is used in eco-design, to evaluate products and energy systems, and to develop regulations for recycling
- LCA systematically describes and assesses all the flows to and from the product or system, from nature (Socolof, 2005)

Why LCA?

- Good tool for decision-making
- Identifies key environmental impacts
- Provides a basis for environmental improvements of a system or product

Life Cycle Analysis (LCA) describes and assesses the interaction between nature and the product or system. LCA is a good tool for decision-making, allowing for identification of key impact processes and providing a basis for environmental improvement. The main steps in LCA are:

1. Goal and scope definition.

2. Inventory analysis: Detailed data collection on input and output of material, energy and other resources for the production process, including disposal.

3. Impact assessment, involving understanding the environmental relevance of input and output.

4. Evaluation and interpretation (Curran, 2006).

The goal and scope section describes why the study is being carried out, how detailed it should be and how the results should be presented. In the goal and scope section the functional unit, reference flow and the system boundaries should be defined. The functional unit is a measure of the function of the studied system and it provides a reference to which the input and output can be related. This enables comparison of two different systems. The choice of the system boundaries is important for the LCA-study, since it is by its boundaries the environmental impact of the system is defined (Eyjolfsdottir et al., 2003). The ISO standards for LCA are: ISO 14040:2006, Environmental management, Life Cycle Assessment, principles and framework ISO 14044:2006, Environmental management, Life Cycle Assessment, requirements and guidelines.

A Life Cycle Analysis is a good tool for measuring the environmental impact of a product from "cradle to grave"; however there are some environmental effects which can not be captured by the analysis. The Life Cycle Analysis focuses on material and energy flow to and from the power plant. LCA does not consider the site specific geographical circumstances, possible effects of subsidence, possible increase in seismic activity, aesthetic concerns and noise pollution (Michaelis, 1998). These factors are dealt with in the Environmental Impact Assessment (EIA). Other factors like the effect of a catastrophe or accidents should be addressed with the appropriate risk assessment.

4 Environmental effects of geothermal energy production

Any type of energy production will effect the environment, but the extent of this impact depends on the energy source and technology used.

Following is a list of the advantages and disadvantages of geothermal energy utilization with regards to environmental effects.

Advantages

- Renewable energy source.
- Small emissions of greenhouse gases compared to fossil fuels.
- In many cases small areas of land occupied.
- Possibility of co-generation of electricity and thermal energy.

Disadvantages

- Noise due to escaping steam.
- Smell of escaping gases.
- Aesthetic concerns.
- Possible negative effects of waste water (if water is not re-injected)
- Possible land subsidence.
- Possible seismic effects of re-injection.
- Release of waste heat.
- Release of several gases including sulphur and greenhouse gases
- Solid waste.

Even though geothermal energy is considered to be a relatively clean energy source with limited greenhouse gas emissions there are environmental concerns regarding utilization. This analysis looks at emissions to air, soil and water from the construction phase of the power plant, during the operation and to the end of life of the power plant. Emissions in the operational phase are not in any way caused by combustion of any kind. Emissions of CO_2 and H_2S occur naturally at the geothermal areas but increase or decrease in emissions has not been measured before and after the geothermal plant has been built. Environmental issues like land use and land subsidence are not included in this analysis.

5 Nesjavellir power plant

5.1 History

The Nesjavellir geothermal field is a high enthalpy geothermal system within the Hengill central volcanic area in South-West Iceland. The field was developed during 1965-1990 to provide Reykjavik and the surrounding towns with hot water for space heating. In Figure 2 there is a map of the Nesjavellir area (Orkuveita Reykjavíkur, 2004). The planning and design of Nesjavellir power plant started in 1986, after a period of successful test drilling (Ballzus et al., 2000). Great amount of information was collected on the area, and a pilot plant was build. The production of thermal energy started in 1990 and in 1998 the electricity production started at Nesjavellir. In 2002 Nesjavellir was a co-generating power plant with a capacity of 90 MW of electricity and about 200 MW of thermal energy in the form of hot water. However, the power plant did not produce at its full electrical capacity in the year 2002. Nesjavellir produced on average 237 MW of thermal energy and 73.8 MW of electricity in the year 2002. This means that the electricity production was around 23% and that thermal energy was 77 % of the total energy production capacity. (Information from Orkuveita Reykjavíkur) Parameters describing Nesjavellir power plant in the year 2002 are shown in Table 1. The Nesjavellir power plant has, as mentioned, been enlarged and is now producing 120 MW of electrical energy.

Figure 2. The Nesjavellir area, figure from Orkuveita Reykjavikur (Orkuveita Reykjavíkur, 2004)

Table 1. Parameters describing Nesjavellir power plant in the year 2002.

Information from Orkuveita Reykjavikur	
Location:	30 km north east of Reykjavik
Opening year:	1990
Production wells:	14
Re-injection wells:	3
Electricity capacity	90MW
Thermal energy capacity	200MW
Total electricity generation 2002:	618,034,368 kWh
Total thermal energy generation 2002:	1,986,476,993 kWh
Total energy generation 2002:	2,604,511,362 kWh
Expected life time:	50 years

5.2 Power production processes

In 2002 geothermal fluid was pumped from the 14 holes in the Nesjavellir area, holes which are around 2000 m deep. The temperature and energy content varies between the holes (Mailänder, 2003). The fluid temperature can reach temperatures of up to 300°C with a pressure from 10-40 bars. The average enthalpy figures are frequently around 1000 kJ/kg. The production wells vary from 1000-2200 m depth and the temperature is in the range 270–360°C. The enthalpy varies also and is in the range 1500-2600 kJ/kg for different wells. The initial average enthalpy was 1700 kJ/kg from the wells at Nesjavellir. The composition of the geothermal fluid is highly variable from the wells and can have different chemical properties. The composition depends mostly on the temperature of the fluid but also on geological surroundings (Gislason, 2000).

Geothermal steam and water from the production wells are gathered in a central separator station. The fluid is separated into water and steam and the steam is transported through pipes to the turbines. On the way, moisture separators are installed to remove any moisture that could be left in the steam. The turbines have a rated capacity of 30 MW. Each turbine requires around 2 kg/s of steam at a pressure of 12 bars to produce 1 MWe (Gislason, 2000).

Fresh groundwater is taken from around 5 wells; this water is first used in the condensers to cool down the exhaust steam from the turbines and to preheat the fresh water. After passing through the condenser, the water is transported to the heat exchangers where it is heated up with the water that was separated from the steam. This kind of utilization releases less heat to the atmosphere than conventional geothermal power plants. (Ballzus et al., 2000)

The main processes used at Nesjavellir are:

- Pumping of geothermal fluid and cold ground water from wells.
- Separation of the steam and water.
- Steam flow to the turbine which turns the generator.
- Cold ground water goes to heat exchangers and to district heating
- Pumping of water to Reykjavik

Table 2 shows the mass and energy flow for different phases and in Figure 3 the flow of the geothermal fluid and water through the power plant is schematically shown.

Table 2. Mass and energy flow through the power plant in 2002.

Information from Orkuveita Reykjavikur **Process**	**Kg/s**	**MW**
1.Geothermal fluid from wells	316,5	568,6
2. Steam I	152	427,3
3. Geothermal water	164,6	141,3
4. Excess steam II	9	19,2
5. Excess water from wells	57,5	49,2
6. Steam to turbine	143	408,1
7. Water to heat exchangers	107,1	92,1
8. Cold ground water	1434,5	61,3
9. Heated water	668,1	237,2
10. Heated cooling water	771,4	193,5
11. Degassing	-	-
12. Electricity produced	-	73,8

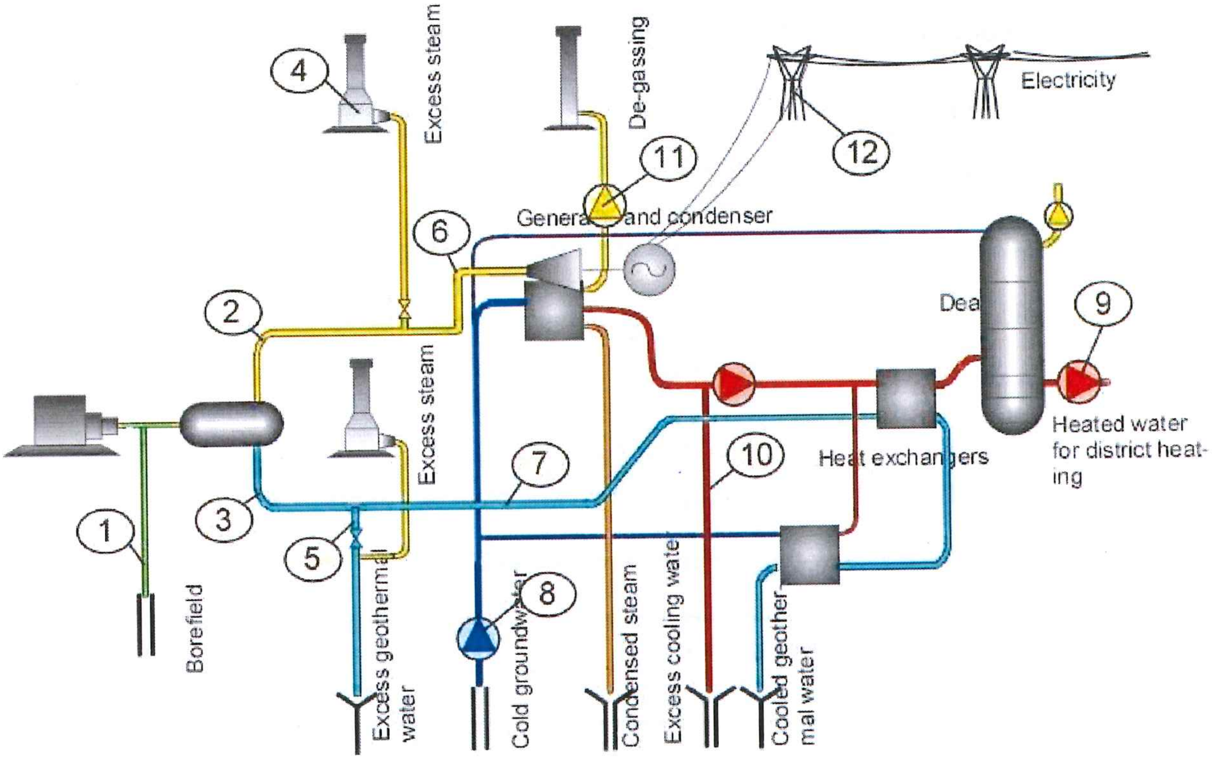


Figure 3. Flow chart of the geothermal fluid through Nesjavellir power plant, figure from Orkuveita Reykjavíkur. All the production steps are included in this analysis, except step 12, transport of electrical energy. Further boundaries are shown in Figure 5.

5.3 Power distribution

The electricity delivered to the Icelandic electricity net from Nesjavellir has the voltage 132 kV. The construction of electrical transport cables to Reykjavik is not considered in this LCA. The electricity is transported to Reykjavik by high voltage lines. The power transport capacity of the line is 110 MW and the line is 31 km long. About 2.5 km of the line is an underground cable, (Ballzus et al., 2000). The hot water, with a temperature around 83°C is pumped to the storage tank at Háhrygg (Nesjavellir area) and from there through the transportation pipe (30km) to distribution tanks at Reynisvatnsheidi near Reykjavík. The transport pipe from Nesjavellir to Reynisvatnsheiði transports around 700 l/s of hot water, for the production capacity of 2002. The pipe is constructed for a 1700 l/s transport capacity. From Reynisvatnsheidi the water is distributed in Reykjavik by Orkuveita Reykjavikur. The transport pipe is a large part of the total construction of Nesjavellir power plant, thus the construction of this pipe is taken into consideration in special parts of the analysis.

5.4 Wastewater disposal from Nesjavellir

Considerable amount of wastewater, with temperatures from 46-100C°, is produced during the energy production at Nesjavellir. This wastewater is either pumped back into the ground through shallow holes or disposed of into the Nesjavellir stream. (Snorrason et al., 2004) This stream finds its way some 3.8 km through lava fields into Lake Thingvallavatn. Notice that this is the excess water that is not used for thermal energy distribution, like most of the warm wastewater. In this geothermal fluid, concentrations of SiO_2, As, Al and B are elevated. However, according to Wetang and Snorrason (2005), the concentration of the chemicals is diluted before the water reaches the lake and there is no detectable rise or accumulation of trace elements in the sediments, vegetation in the water or fish at the geothermal influenced sites. Also Olafsson (Olafsson, 1992), measured the quantities of various trace elements in lake Thingvallavatn and he concluded that before the chemicals could reach the lake they are lost in to the atmosphere. The chemicals are then modified by reactions and diluted to such an extent that there is little cause for concern, except possibly in the case of arsenic. According to Olafsson (Olafsson, 1992), the arsenic should be monitored closely. With increased power production, waste water increases. It is important to follow the destination of the waste water and monitor its impact on the surrounding environment.

According to Snorrason et al. (2004) water temperature at outflow sites in Lake Thingvallavatn are much higher at shallow depths (< 1 m) than at control sites due to warm effluents from the geothermal power plant at Nesjavellir. This impact of this warm water is not considered in this analysis.

Guðjón Atli Auðunsson, at ICI, applied for a grant in 2008 to monitor mercury in lake trout in Lake Thingvallavatn and other lakes in Iceland. Larger trouts have been found to contain relatively high concentrations of mercury in Thingvallavatn but little information is available for other lakes in Iceland, especially regarding large trouts. The reasons for this elevation in large trouts in Thingvallavatn are not known but the aim of the project is to reveal possible causes. The causes might for example be high tropic level of these large individuals and possibly release of geothermal water to Lake Thingvallavatn

6 Structure and Inventory Information for the LCA of Nesjavellir

6.1 Purpose of study

The main goal of this LCA study is to analyze the overall environmental effect of producing 1kWh of electrical power and 1kWh of co-generated power in the geothermal power plant at Nesjavellir, Iceland. Harnessing of geothermal energy is increasing every year and thus it is important to know the key environmental factors of utilization of geothermal energy. Such knowledge is of advantage for strategic decision making during design of new sites and to minimize the overall environmental effects at existing sites. A similar study has been performed at Bagnore3 power plant in Italy and results have been published (Enel, 2006).

This project has taken a broader view than first planned, by including the effects of the thermal energy production. An LCA identifies not only the overall environmental impact, but also where it is generated in the production chain. This information can help the energy producer to minimize the overall environmental effects from the production and be of help in future decision making.

6.2 Functional unit

The functional unit has been chosen as 1kWh of energy produced which is a unit that most users of energy are familiar with and is furthermore a unit that can be used for both electricity and thermal energy.

The energy produced at Nesjavellir and transported to town is electricity and thermal energy. Some geothermal power plants have only market for produced electricity. Results are thus presented in two ways that is for mere production of electricity and for co-generated thermal and electrical energy.

The environmental effects of the co-generation are the total environmental effects of the electrical and thermal production divided to the total energy production, both thermal and electrical.

In the reference year, 2002, the average production was 237 MW of thermal energy and 73.8 MW of electric energy. The total electrical power production was 618,034,368 kWh and 1,986,476,993 kWh of thermal energy, total 2,604,511,361 kWh during the year 2002.

6.3 Boundaries

The system boundaries follow the energy production and material use for the production of raw materials for the construction of the power plant, operations and finally dismantling of the power plant. The life cycle of the power plant is divided into three phases:

- Construction phase
- Operation phase
- End-of-life phase

In Figure 4 the division of the analysis is shown. Test drilling at site, step A in Figure 4 was not included in this analysis. The construction phase is the phase when the power plant is built, and then operational phase is when the power plant is producing energy. The last phase is the end-of-life phase, when the power plant is dismantled. The end of life phase is estimated and simplified. In the following section further details of boundaries and simplification for each phase is given.

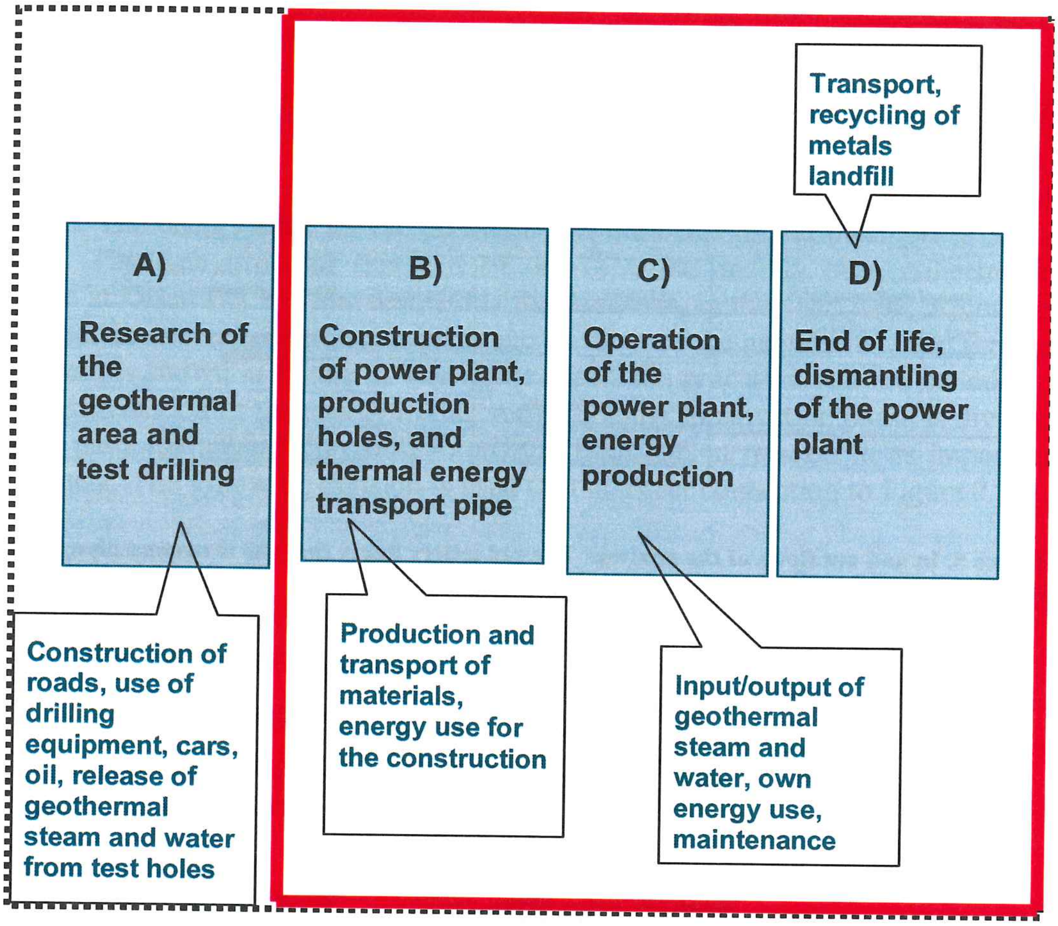


Figure 4. Different phases in the geothermal power production, B) the construction phase, C) the operation phase and D) the end of life phase are the phases inside the red line and are included in the analysis. Phase A), the research of the geothermal area and test drilling, is not included in this analysis.

In Figure 5, the in and out flows of the analysis are shown and simplified boundaries of the analysis are showed in Figure 6 where the steps inside the red line have been included in the analysis.

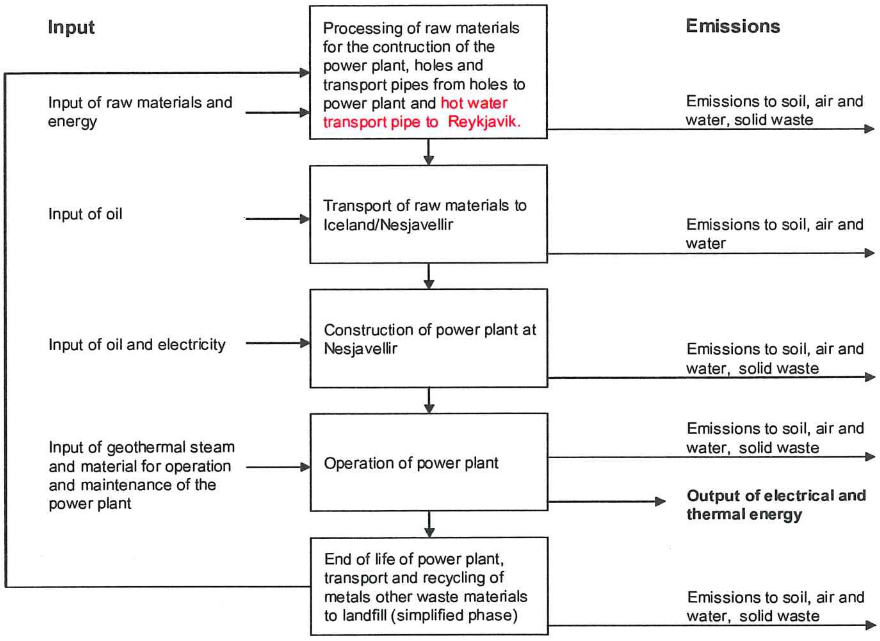


Figure 5. In and out flows of the analysis. The red letters imply that the transport pipe is not always included.

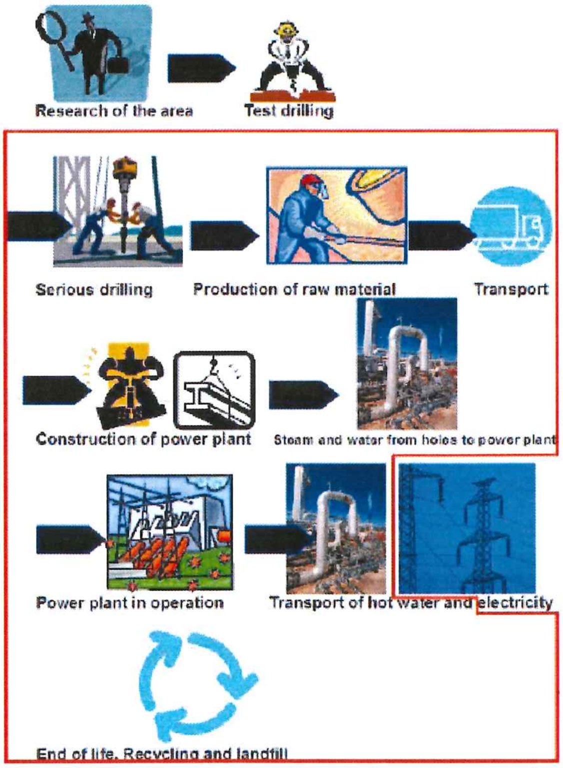


Figure 6. Simplified boundaries of the analysis, the steps included in this LCA are inside the red line.

6.4 Modeling in Gabi4

The modelling of this LCA is carried out with a program called Gabi4. The Gabi4 software is based on a modular concept. The modelling of the Nesjavellir power plant in Gabi4 was influenced by the setup from Ellen Mälenders Gabi4 modelling from her work: "Life cycle analysis of hydrogen infrastructure for fuel cell driven buses in the public transport of Reykjavik" (Mälender, 2003). The modelling consisted of making plans, processes and flows and their functionalities that establish the modular units.

6.5 The construction phase structure and inventory information

In this phase, all the material used for building the wells, houses, equipment etc. is examined. The energy used for the production of the material and transport to Iceland is included. The data used for this part of the LCA has mainly been collected by an employee at Orkuveita Reykjavikur, Edda Sif Aradóttir, in the year 2003. A chart of the main structure of Nesjavellir power plant and the flow of the geothermal fluid through the power plant is shown in Figure 7. The figure shows the processes that are included, from holes to distribution of the energy to the consumer. The construction phase is divided into different parts that make it possible to analyze each part in relation to its impact on the environment. The following division is used (not in direct connection to Figure 7.):

1. Separator station
2. Powerhouse building
3. Heat station (inside powerhouse)
4. Electric station (inside powerhouse)
5. Transport pipe to Reykjavik (Reynisvatnsheiði)
6. Production holes
7. Re-injection holes
8. Staff house
9. Grámelur (pumping station)
10. Electric cables
11. Transport
12. Storage house

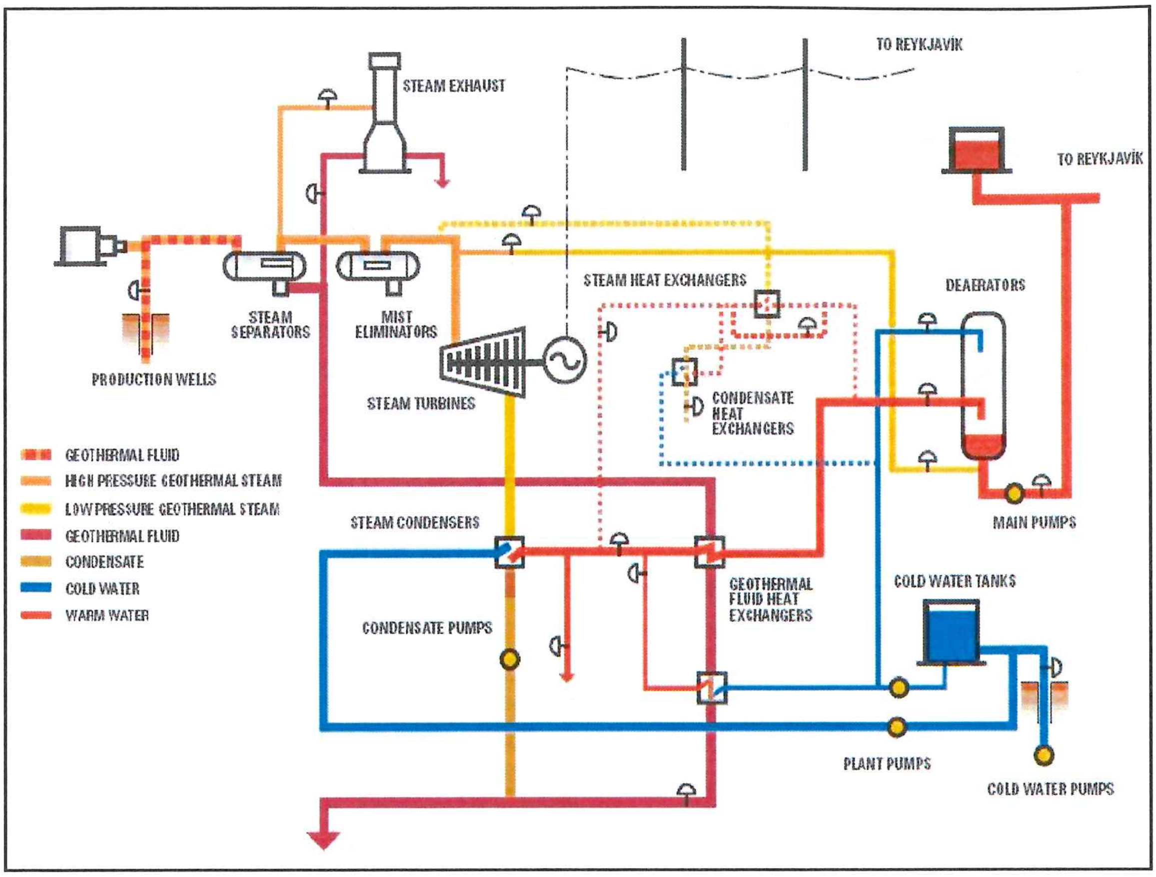


Figure 7. Chart of the path of geothermal fluid through Nesjavellir power plant, figure from Matthiasdottir, 2006, note that the transport of electrical energy in this figure is not included in the analysis.

Estimations and simplifications

The life time of the initial construction is estimated to be 50 years, with estimated maintenance of 2% each year based on the initial construction material used.

Two more scenarios for the life time of the power plant were made, a life time of 30 years and 70 years respectively.

Scenarios were made that included the effects of the construction of the transport pipe when the co-generation of electric and thermal energy was inquired. It is specially mentioned in the results where the transport pipe has been included. When the transport pipe is included, it is only considered to go to Reynisvatnsheidi. Thus, distribution pipes and stations inside Reykjavik are not taken into consideration.

The focus in this phase was mainly on the construction materials and the equipment needed for power production. It is assumed that the metals are imported by ship 2000 km and trucked 500 km from the production site. It is assumed that most of the material is coming from the European mainland. Transport in Iceland is included in the 500 km truck transport estimate. Transport of concrete is not considered, since most of the material for the concrete is from mines near site. The trucks are estimated to have an average operational ratio of 85% as details regarding transport were not available. Details on furnishing the staff building and control house are not included. The building of roads to and from the power plant is not included in the analysis. Information from all the different types of metals used in the construction phase were not available from the Gabi4 database, thus approximations were made. It is estimated that about 1/6 of the green house gas SF_6 is released during the construction phase into the atmosphere.

Electrical energy production versus co-generation

For the mere production of electricity it is not needed to pump cold water from wells, to have a heat station or the transport pipe for hot water to Reykjavík, see figure 7.

6.6 The operational phase structure and inventory information

The operational phase includes the input and output during the operation of the power plant. The main material flow through the operating power plant is the flow of geothermal steam and water. The operational phase was divided into the following categories: geothermal fluid and gases, maintenance, oil use, re-injection holes and production-holes. Figure 7 shows the flow of geothermal steam and water through the power plant. The data for chemical composition of geothermal steam and water through the Nesjavellir power plant is provided by Orkuveita Reykjavikur and also the data for use of energy and materials for maintenance.

Estimations and simplifications

Yearly maintenance of the power plant is, as mentioned, estimated to be 2% of the initial construction materials. It is assumed that for continuation of the 2002 production capacity level throughout the expected lifetime of 50 years, one production hole will have to be drilled every four year and one re-injection hole every ten years. The release of steam from unconnected wells (steam that goes directly into the atmosphere) is also taken into consideration. In Appendix 1, information on the chemical composition of the geothermal steam and water from Orkuveita Reykjavikur is given. The effects of warm waste water are not included in the analysis.

Table 3. Hydrogen sulphide emission from Nesjavellir in the years 2002, 2003 and 2004.

Year	2002 [Tones/year]	2003 [Tones/year]	2004 [Tones/year]
Hydrogen sulphide emissions	8636	5941	5084

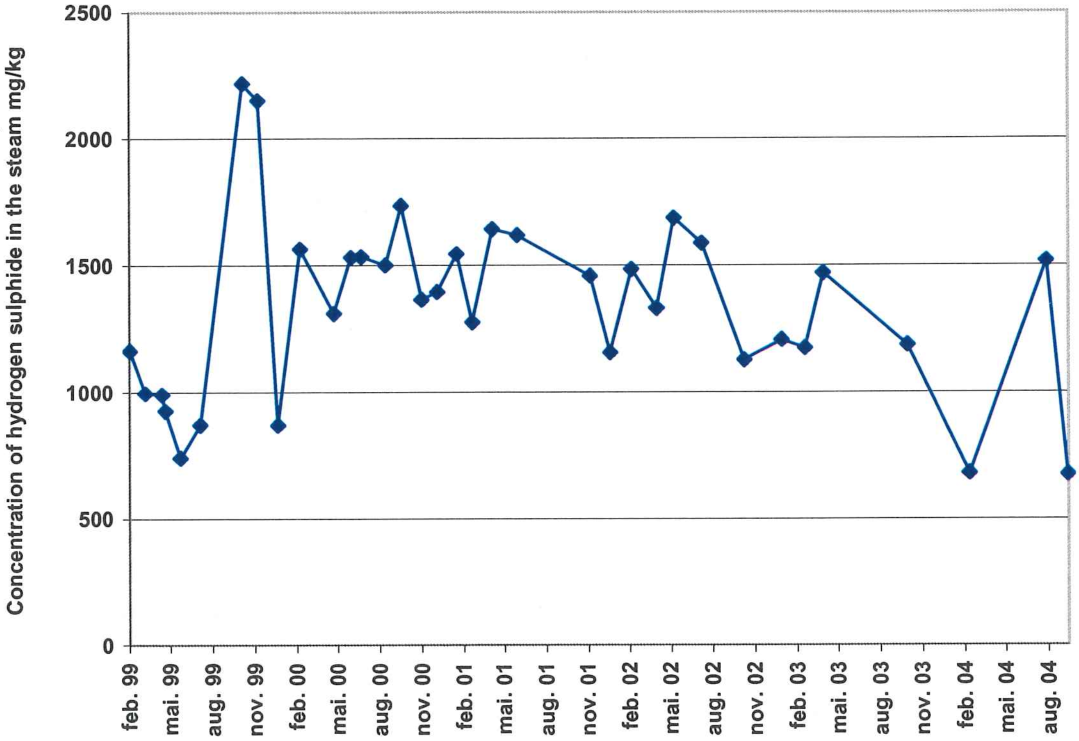


Figure 8. The concentration of hydrogen sulphide in milli grams per kg of steam is constantly changing. Data from Orkuveita Reykjavikur.

Hydrogen sulphide and carbon dioxide in the steam

The hydrogen sulphide emissions and concentration in the steam from Nesjavellir are not constant. Table 3 shows that significant variations are in the release of hydrogen sulphide in the years 2002-2004. These emissions changes are both due to different amounts of steam released and also different levels of hydrogen sulphide concentration in the steam. Different concentration of hydrogen sulphide over a time period from February 1999 to august 2004 is shown in Figure 8. From the figure it is clear that measured concentration levels can be quite different from one time to another. In Section 7.3 there is a discussion on hydrogen sulphide and its fate in Iceland. In Section 7.4 there is a model for the changes of the concentration of carbon dioxide. A decrease of the concentration of carbon dioxide has been detected, but is difficult to say how it will change in the future.

Electrical energy production versus co-generation

The flow of geothermal fluid is the same for the electrical production with or without the production of hot water. The flow of cold water for distribution is not a part of the electrical production and is therefore not included when looking separately at the electrical production. The percentage of maintenance is still the same, i.e. 2% of the initial construction phase material used for the electrical production utilities.

6.7 The end-of-life phase structure and inventory information

At the end of life scenario all manmade structures go to landfill at site except the metals (steel, copper, iron and aluminium). The material used in the boreholes will be left at site. The following estimation was made; that 90 % of the metals from the construction phase will be recycled. It is also estimated that the metals will be transported 2000 km by ship and 500 km by truck on the mainland, with a load of 85% to the recycling facility where they will be recycled. Metals used in maintenance are not taken into consideration in this phase. This is the current way of handling similar projects in Iceland. Hopefully in 50 years, the recovery of materials will be more advanced in Iceland. The recycling processes used are those included in Gabi4 program.

7 Impact assessment and evaluation

In this section the results from the analysis are presented. Results are given for each phase separately and for the combined phases. The results are presented in different ways. One is by using the evaluation method, Eco-indicator 95. The second is using mass of equivalents for selected impact categories with the CML2001 method. The third is by presenting the actual mass figures of selected chemicals and chemicals compounds. Mass figures are only presented for the construction and operational phase and are in Appendix 2. The CML2001 method is developed by the Centre of Environmental Science in Leiden Netherlands in 2001. (Guinée et al., 2001)

The selected environmental impact categories with CML2001 are:

- Global warming potential (GWP), kg CO_2 equivalents. Emissions to air which influence the temperature of the atmosphere.
- Acidification potential (AP), kg SO_2 equivalents. Emissions to air and soil which cause acidification of rain, soil and water. (In both CML2001 and in the eco-indicator, the conversion rate of hydrogen sulphide to sulphur dioxide is 1.88 (Fischer et al, 2005) see further discussion in Section 7.3)
- Eutrophication potential (EP), kg Phosphate equivalent. Eutrophication of lakes, rivers and soil.
- Photochemical ozone creation potential (POCP), kg Ethane equivalent. Emissions to air which lead to ozone production in the troposphere.
- Ozone layer depletion potential (ODP), kg CFC11 equivalent. The increase in ultraviolet radiation on Earth caused by high-altitude decomposition of the ozone layer.

The result figures are very small each kWh, thus the results from the impact categories are presented in grams of the above mentioned equivalents, not kilograms.

Eco-points 95

The Eco-indicator of a material or process is a single score environmental assessment giving one figure to indicate the total environmental impact of a material or process. The higher the indicator, the greater is the environmental impact. Here the results are calculated according to the Eco-indicator 95 method. The Eco-indicator is expressed in milli-points per functional unit. The ecopoints 95 method is a method that was developed by PRé Consultants and DUIJF Consultancy BV in Netherlands. It has now been extended to eco-points 99. The eco-points method is a tool to analyze the environmental pollution of products or ideas to find opportunities for improvements. The impact categories in the eco-indicator are:

- Greenhouse effect
- Ozone layer depletion
- Acidification
- Eutrophication
- Heavy metals (lead equivalents)
- Carcinogens (PAH equivalents)
- Winter smog (SO_2 equivalents kg)
- Summer smog (POCP equivalents)
- Pesticides

The method that has been developed is a certain weighting method between the different environmental impact categories based on the damage done on the eco-system, health impairment and fatalities. From the homepage of PRé Consultants in Netherlands a full report on the weighting method used in the eco-indicator 95 is available (www.pre.nl/download/EI95FinalReport.pdf).

7.1 Results for all phases

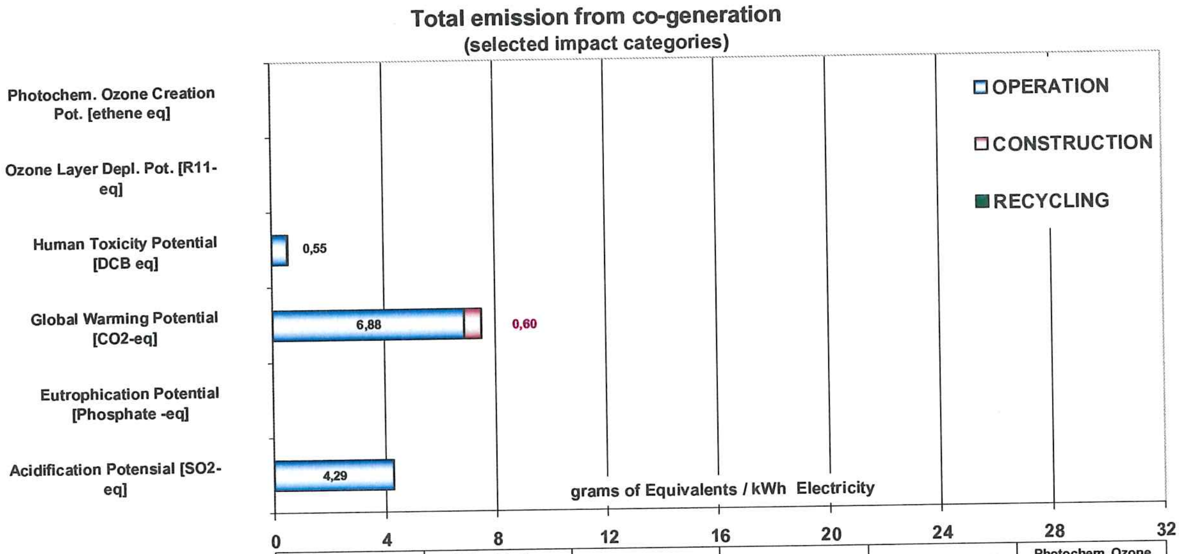
In Table 4 the total emissions of selected impact categories in grams of the specific equivalents per kWh for the different energy production options are listed. It includes electricity and co-generation with and without the transport pipe to Reykjavik. The lifetime of the power plant is estimated to be 50 years. These figures are presented graphically for the co-generation with the transport pipe in Figure 9 and the electrical production in Figure 10.

From Figure 9 and 10 it is evident that a predominant part of the environmental impact is due to the operational phase, where the emissions of carbon dioxide and hydrogen sulphide influencing the global warming and acidification potential respectively. The construction phase has also a significant impact on the global warming category.

When the emission values are compared in Figures 9 and 10, it is clear that there is a great positive effect per kWh of using the hot water that comes from the electricity production for thermal energy production.

Table 4. Total emissions to air, of selected impact categories.

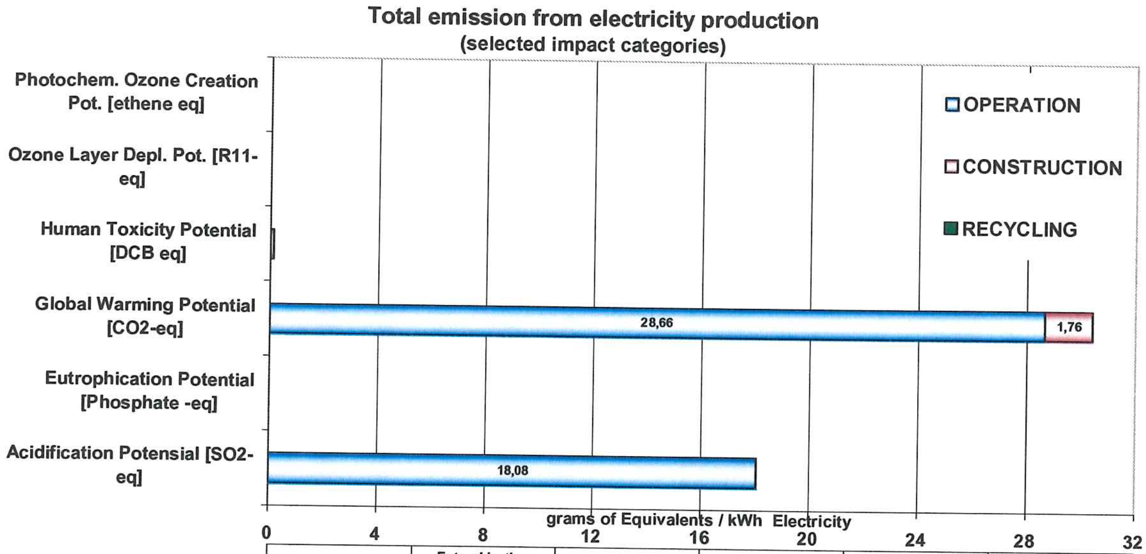
Impact category	Co-generation with transport pipe (g / kWh)	Co-generation (g / kWh)	Electricity (g / kWh)
AP - SO_2 equivalent	4,29	4,29	18,1
EP - phosphate equivalent	5,94*10-4	5,30*10-4	2,21*10-3
GWP - (100 years) CO_2 equivalent	7,46	7,29	30,3
HTP - DCB equivalent	5,73*10-1	5,67*10-1	8,87*10-2
ODP - R11 equivalent	1,69*10-7	1,50*10-7	6,30*10-7
POCP - ethane equivalent	7,52*10-4	6,72*10-4	2,80*10-3



	Acidification Potensial [SO2-eq]	Eutrophication Potential [Phosphate -eq]	Global Warming Potential [CO2-eq]	Human Toxicity Potential [DCB eq]	Ozone Layer Depl. Pot. [R11-eq]	Photochem. Ozone Creation Pot. [ethene eq]
🟩 RECYCLING	-5,35069E-05	-9,64731E-06	-0,031306688	-0,008116228	-7,28646E-10	-1,75093E-05
☐ CONSTRUCTION	0,001143962	0,000214951	0,603420336	0,034780796	6,65732E-08	0,000291356
☐ OPERATION	4,292779518	0,000388901	6,883521855	0,546096156	1,03122E-07	0,00047814

Figure 9. Total emission of selected impact categories in grams per kWh of co-generation. The transport pipe to Reynisvatnsheidi is included. Negative values indicate positive environmental effects.

Both Figures 9 and 10 show the amounts of the specific equivalents per kWh in grams. It is clear from Figures 9 and 10 that emissions for each kWh generated that the highest values are from the greenhouse gases (that lead to global warming). It is clear that the values of the impact categories global warming and acidification potential from the operational phase are the dominant categories for the co-generation. The construction phase has an effect on the global warming category, but almost none on other impact categories.



	Acidification Potensial [SO2-eq]	Eutrophication Potential [Phosphate -eq]	Global Warming Potential [CO2-eq]	Human Toxicity Potential [DCB eq]	Ozone Layer Depl. Pot. [R11-eq]	Photochem. Ozone Creation Pot. [ethene eq]
■ RECYCLING	-0,000146567	-2,64261E-05	-0,085755921	-0,022232137	-1,99592E-09	-4,79618E-05
☐ CONSTRUCTION	0,003254584	0,000596771	1,758919878	0,1092986	1,97788E-07	0,00082895
☐ OPERATION	18,08227812	0,001638151	28,66106872	0,001638151	4,34377E-07	0,002014047

Figure 10. Total emissions of selected impact categories in grams of equivalents per kWh of electricity produced. Negative values indicate positive environmental effects.

Global warming and acidification potential from the operational phase are the dominant categories for the electricity generation. The construction phase has a small effect on the global warming category but almost none on other impact categories. Comparison to figure 9 shows a significant gain with co-generation.

Even though the Global warming potential seems to be the dominant factor when looking at figure 10 this changes when taking one step further in the LCA process. This is shown in figure 11 which shows the eco-points in a weighted contribution of each phase to the environmental impact. Here the hydrogen sulphide (H_2S) emissions from the operational phase (geothermal steam) are the dominant contributor to the largest impact category, Acidification potential. With the eco-indicator the Global warming potential now becomes second to the Acidification potential. This eco-indicator 95 is a European method where the conversion rate of hydrogen sulphide to sulphur dioxide is considered to be 100%.

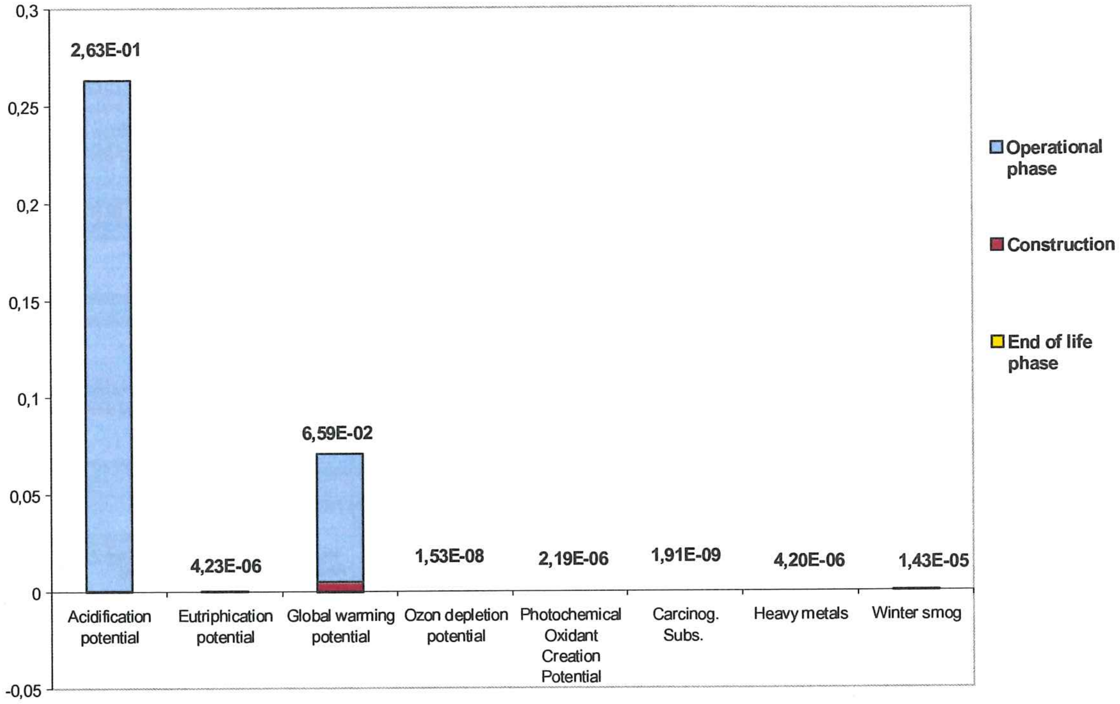


Figure 11. Eco-points (95) distribution for the phases, of electrical energy production. Acidification potential is the largest contributor according to this method. The construction phase has a small impact and most of the total environmental impact per functional unit is due the operational phase.

According to Kristmannsdóttir et al., 2000, this is not the case in Iceland because of the special atmospheric conditions in Iceland. The Icelandic atmospheric conditions are cold, windy and wet climate. The results obtained with these methods show that given a conversion rate of hydrogen sulphide to sulphur dioxide is 100% the largest environmental impact from the energy production at Nesjavellir is due to the emissions of hydrogen sulphide.

In order to further interpret the results from the eco-indicator scenarios, different conversion rates of hydrogen sulphide to sulphur dioxide where used.

Figure 12 show the results from scenarios for different conversion rates of hydrogen sulphide to sulphur dioxide for 0, 5, 25, 50, 75 and a 100 % conversion. It is clear that the acidification is the dominant impact factor if the conversion rate of hydrogen sulphide is more than 25% but if the conversion factor is less than 25%, the global warming category becomes the dominant impact category. Figure 12 show that the overall environmental impacts are very dependent on the conversion rate of hydrogen sulphide to sulphur dioxide, stressing the importance of research in this field. This is discussed further in Section 7.3.

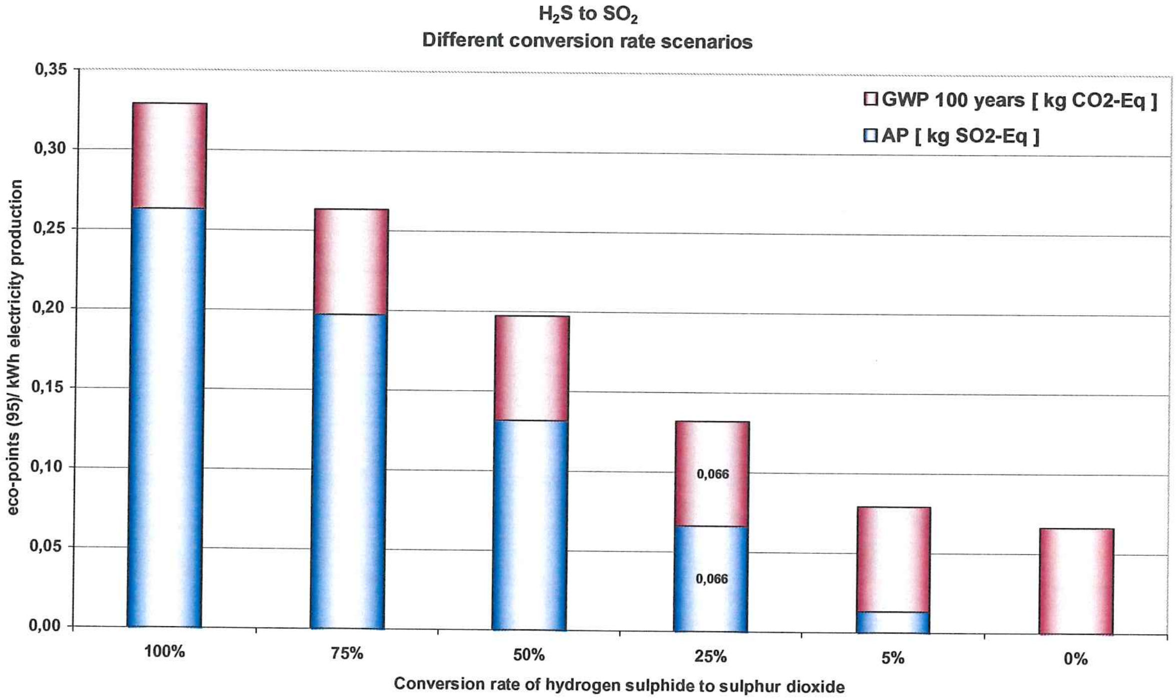


Figure 12. Variation of eco-points (95) for electricity production with different conversion rates of hydrogen sulphide to sulphur dioxide (AP=Acidification potential and GWP=global warming potential).

The eco-points distribution is dependent on the conversion rate of the hydrogen sulphide. If the conversion of hydrogen sulphide is 25% or less, the main impact of the energy production would be the emission of green house gases. It is thus pointed out that the actual conversion rate is very important in order to evaluate the overall effects of the use of geothermal energy. The emission of hydrogen sulphide has the most significant environmental effect according to the eco-point evaluation method. However it is depended on the actual conversion rate, stressing the vital importance of knowing the exact conversion rate of hydrogen sulphide in Iceland.

7.1.1 Construction phase

From section 7.1 it is evident that the environmental effects from the construction phase comes secondary to the dominant impact from the operation phase.

Emissions of the selected environmental impact categories from different parts of the construction phase are shown in Figure 13.

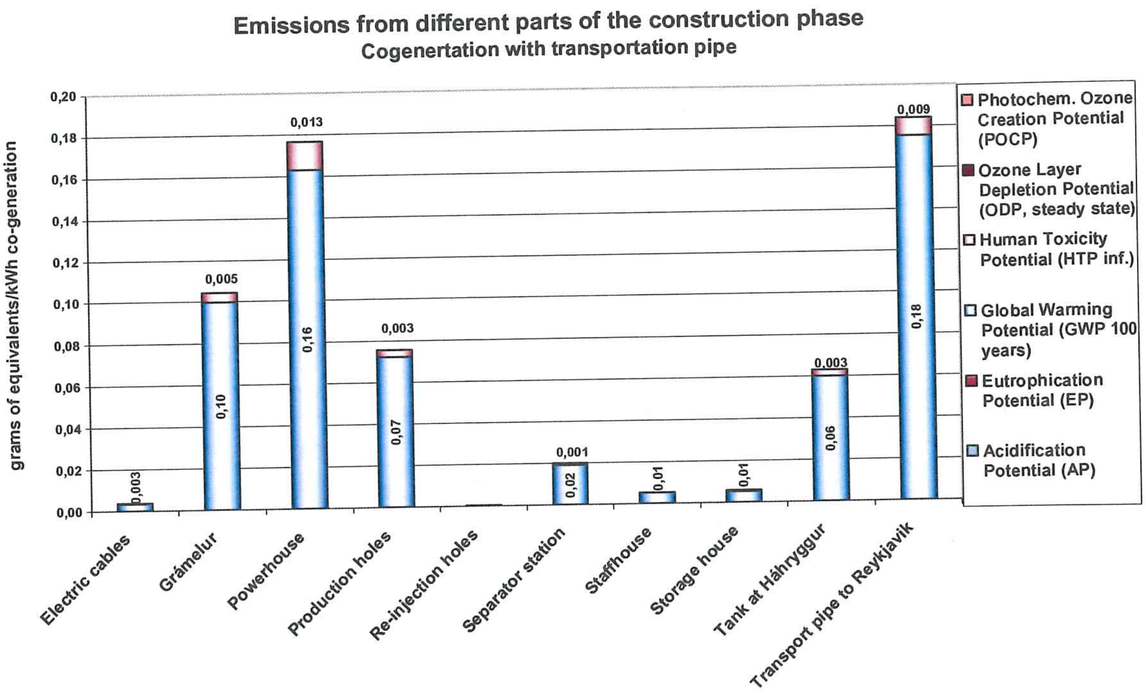


Figure 13. Emissions of different impact categories from the different parts of the construction phase for cogeneration of energy production with the transport pipe to Reykjavik included. The figures are in grams of the specified equivalents per kWh of co-generation. The construction of the transport pipe to Reykjavik has the greatest impact in the construction phase, followed by the power house. The dominant impact category is the global warming due to the production of metals.

It is clear that it is the transport pipe from Nesjavellir to Reynisvatnsheidi that has the largest environmental effect, when looking at co-generation. The largest emission in mass is from the greenhouse gases measured in carbon dioxide equivalents. The power house becomes the largest contributor when looking only at the electricity production. The category "powerhouse" includes all the equipment inside the powerhouse, such as the turbines and the generators.

In Table 5 the total emissions of the selected impact categories are shown in gram/kWh for the construction phase for the different energy production scenarios.

Table 5. Emission of selected impact categories for the construction phase (50 years).

Compound	Co-generation with transport pipe	Co-generation	Electricity
AP - SO_2 equivalent	1,14*10-3	8,0*10-4	3,3*10-3
EP - phosphate equivalent	2,15*10-4	1,50*10-4	6,0*10-4
GWP - (100 years) CO_2 equivalent	0,60	0,43	1,76
HTP - DCB equivalent	3,48*10-2	2,63*10-2	0,11
ODP - R11 equivalent	6,70*10-8	4,78*10-8	2,0*10-7
POCP - ethane equivalent	2,90*10-4	2,1*10-4	8,3*10-4

The dominant impact category, from all the different parts, is the global warming potential, due to the production of metals such as steel, aluminium, copper and iron. The second largest impact categories are the human toxicity potential. Distribution of eco-points for the construction phase is shown in Figure 14. It is clear that when the transport pipe is included, it contributes to around 30% of the total environmental impact of the construction phase.

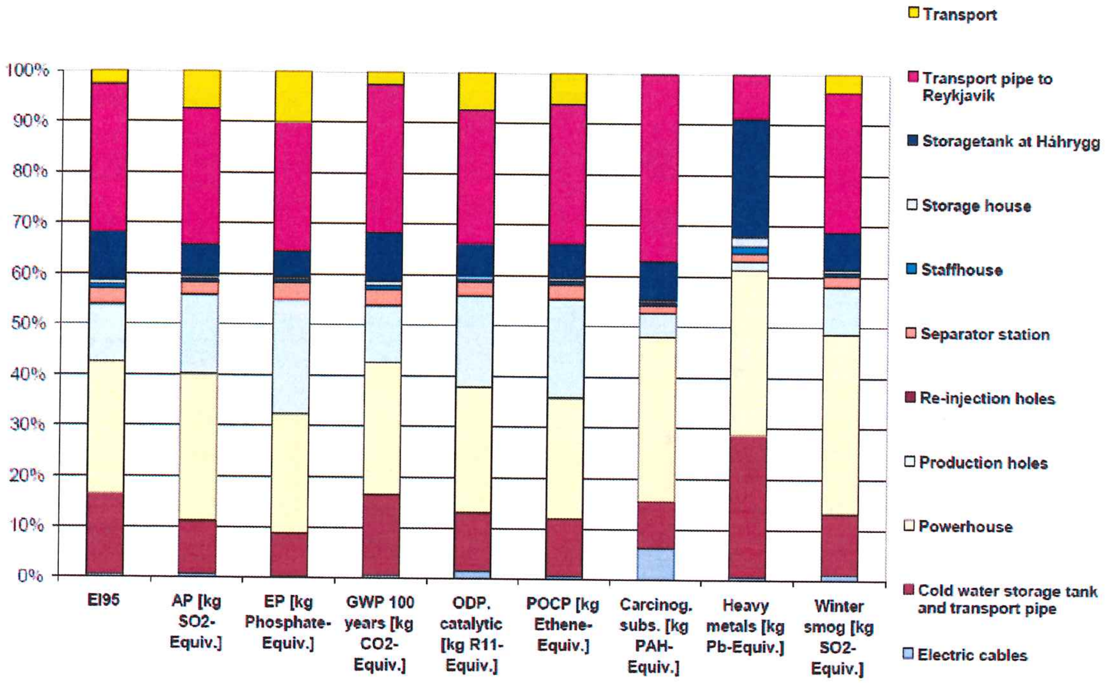


Figure 14. Overview of Eco-Points for the construction phase, including the transport pipe to Reykjavik. The transport pipe and the power house are the largest contributors to the eco-points during the construction phase, followed by the two storage tanks.

The impact of transport of material to and from site is, as seen in Figure 14 less than 5%. The main production processes responsible for the environmental impact from the transport pipe to Reykjavik are shown in Figure 15. It is clear that the production of the steel pipe has the largest impact. This was the results for all the different parts of the construction phase, the production of metals had the most influence.

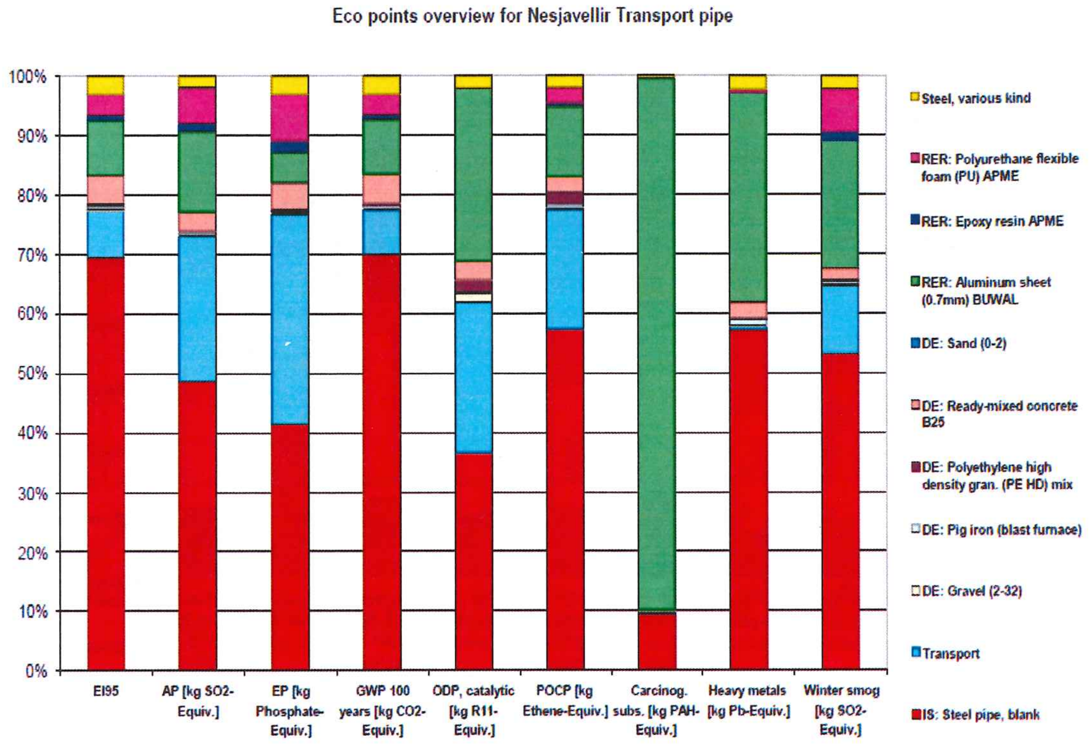


Figure 15. Eco-points (for the largest impact categories) for the construction of the transport pipe. The construction of steel pipe for the transport pipe to Reykjavik is the largest contributor of eco-points for the transport pipe with almost 70% of the impact.

In Figure 16 there are scenarios for different lifetimes of the energy production shown and its effect on the impact of the construction phase measured in emissions of carbon dioxide equivalents.

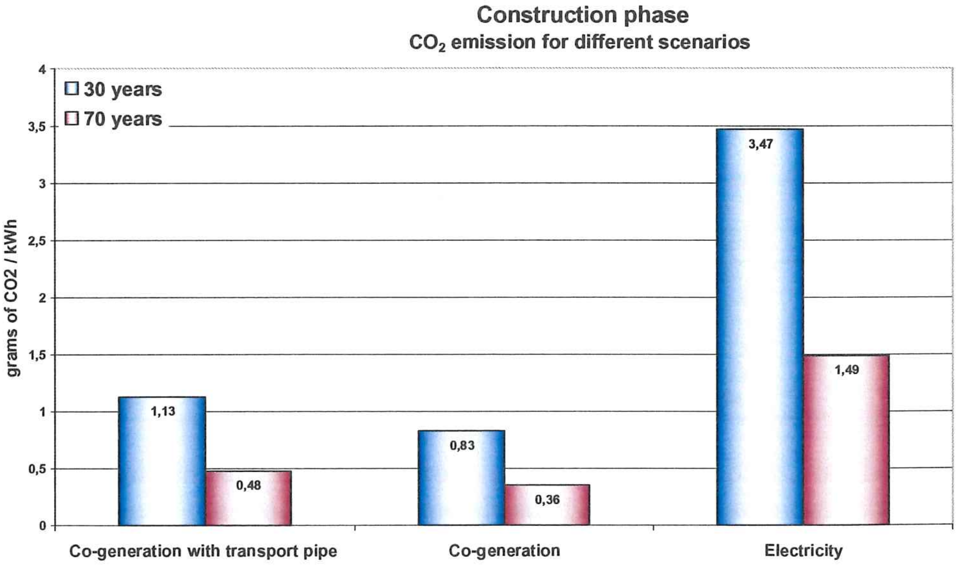


Figure 16. Emission of carbon dioxide for different scenarios for the construction phase.

The environmental effects of construction phase per kWh production of electricity and co-generation lessens with increased lifetime of a power plant.

A significant difference is between the values per kWh of the electrical production and the co-generation. The benefit of utilizing the geothermal steam for co-generation is clear when looking at the environmental effect per one kWh. The results from the lifetime scenarios for 30 and 70 years show that the emission of carbon dioxide equivalents in grams/kWh is in the range from 0.48 to 1.13 g /kWh for combined generation production including the transport pipe to Reykjavik, and 1.49 to 3.47 g/kWh for the electricity production. This shows that the estimated lifetime of the power plant has impact on the results from this phase. It is interesting to see the difference between emissions per kWh of energy for the combined production compared to the electricity production. Numerical values for Figure 16 are in Appendix 1.

7.1.2 Operational phase

From chapter 7.1 fig 10 it is evident in terms of environmental effects it is the operational phase that is most important phase. The distribution of this impact within the operational phase is shown in Figure 17 for the electrical production. It is evident that the dominant impact is the geothermal steam and water. This means that emissions from the geothermal steam and water are the largest single contributor to the overall environmental effects of the energy production. It is also clear that the impact from the geothermal steam and water is mainly due to the acidification potential and the global warming potential (GWP). The secondary contributor is the maintenance of the power plant. Other contributors are the production of re-injection and production holes. The distribution of the impact from the operational phase for the co-generation is very similar to the electrical production, only with lower values each kWh.

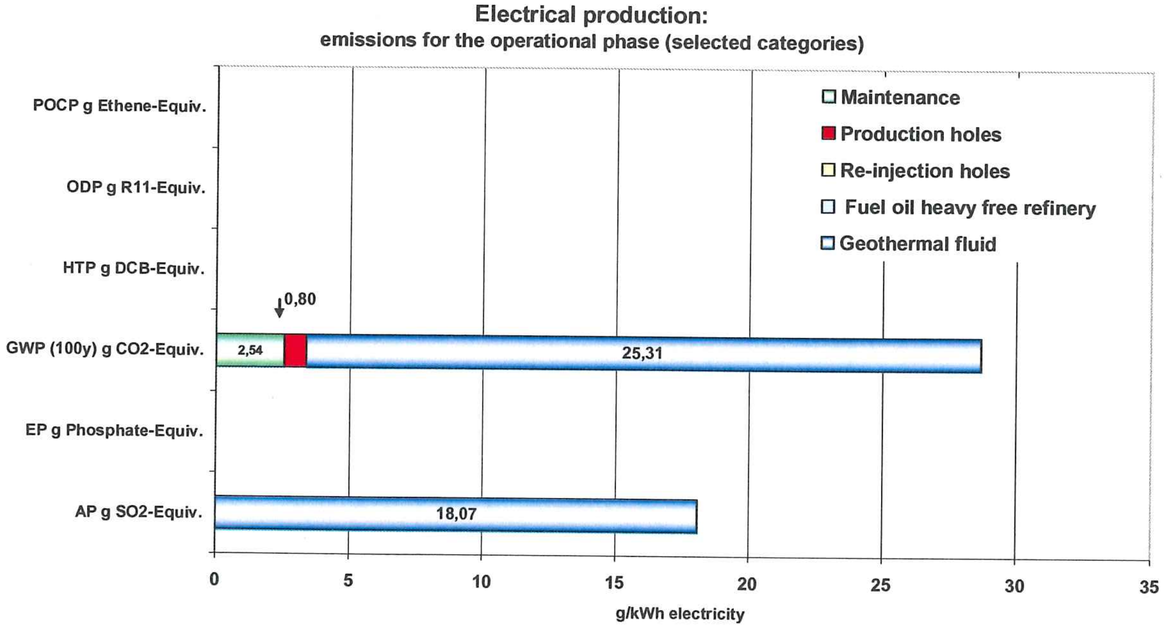


Figure 17. Emission of selected impact categories for the operational phase, electrical production. The figures are in grams of equivalents per kWh of electrical production. Emissions from the geothermal steam have the dominant impact, due to the release of carbon dioxide and hydrogen sulphide.

In Table 6 the total emissions of selected impact categories for the operational phase are listed for the relevant different production scenarios. In Figure 18 these results are shown graphically. From Figure 18 the benefit of utilizing the hot water for thermal energy distribution is clear, by looking at environmental impact for each kWh. In Figure 19 the distribution of eco-points for the electricity production is presented. It is clear that it is the category acidification potential that has the largest impact, when this method is used. Different scenarios that where made in Section 7.1 for the conversion rate of hydrogen sulphide to sulphur dioxide are relevant for this phase, but are not repeated here. Mass figures of selected impact categories from the operational phase are in Appendix 1.

Table 6. Emissions of selected impact categories for the operational phase (50 years).

Impact category	Electricity (g / kWh)	Co-generation with transport pipe (g / kWh)
Acidification Potential (AP) SO_2 equivalent	18,08	4,29
Eutrophication Potential (EP) phosphate equivalent	1,64*10-3	3,89*10-4
Global Warming Potential (GWP 100 years) CO_2 equivalent	28,66	6,88
Human Toxicity Potential (HTP) DCB equivalent	1,64*10-3	5,46*10-1
Ozone Layer Depletion Potential (ODP) R11 equivalent	4,34*10-7	1,03*10-7
Photochem. Ozone Creation Potential (POCP) ethane equivalent	2,01*10-3	4,78*10-4

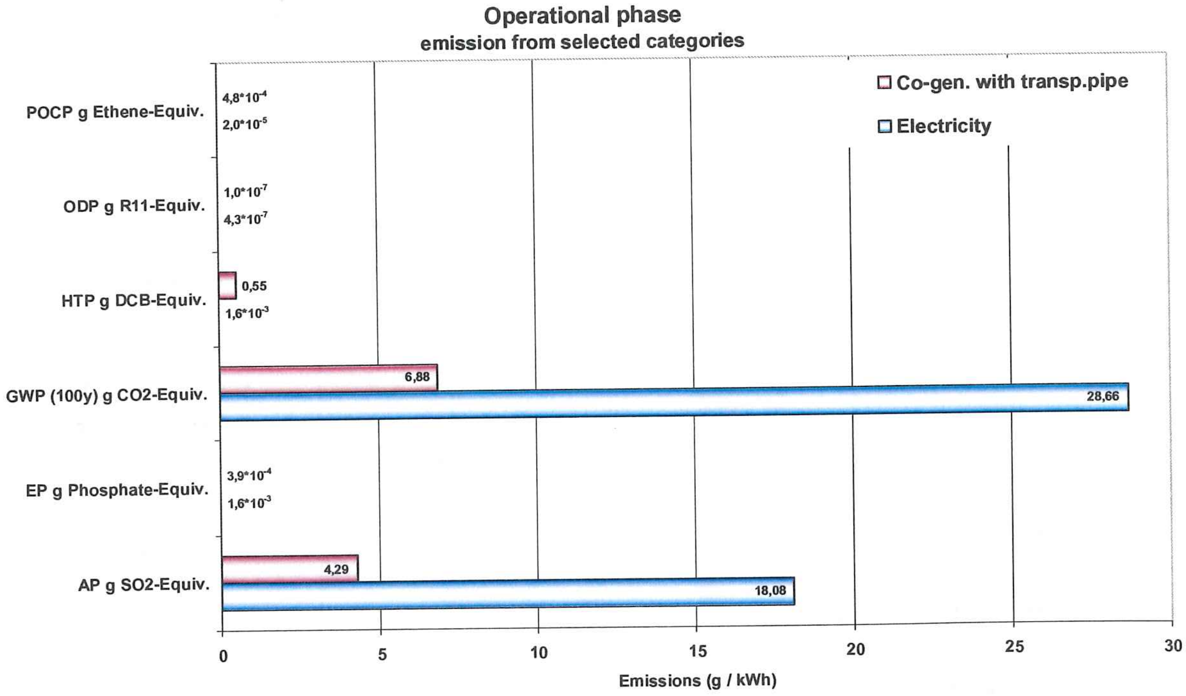


Figure 18. Emissions of selected impact categories for the operational phase in grams of selected impact categories per. each kWh for both the electrical energy production separately and also the co-generation.

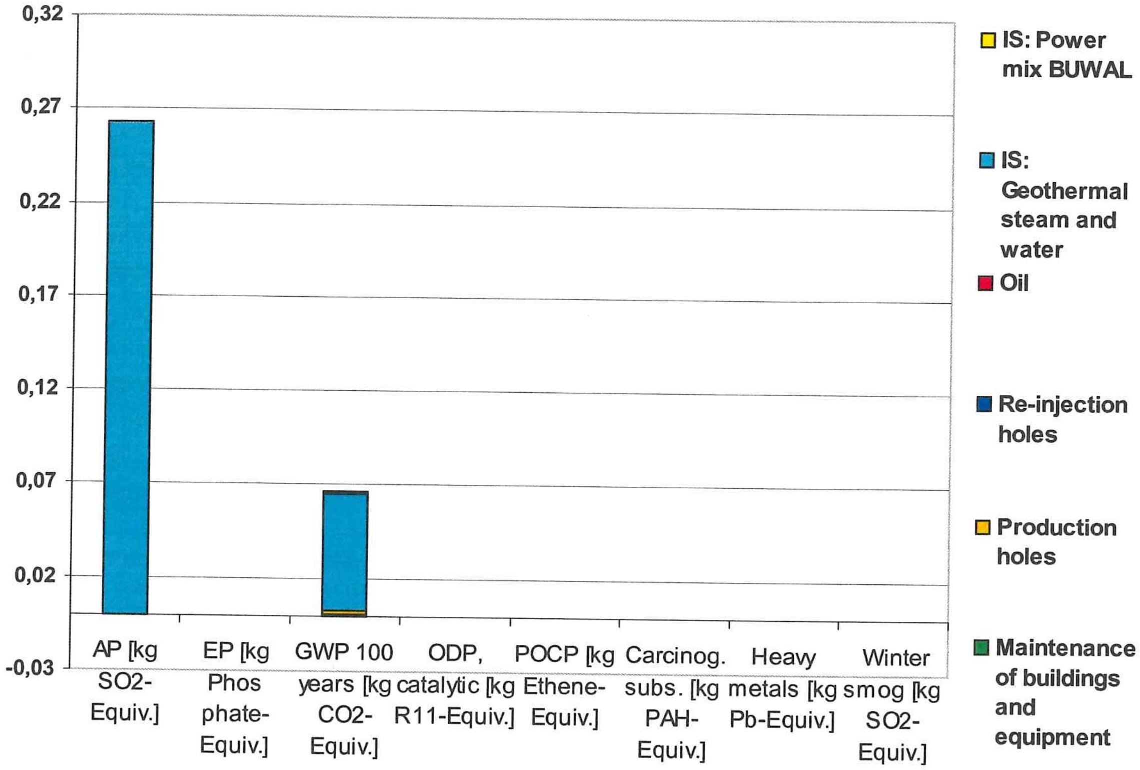
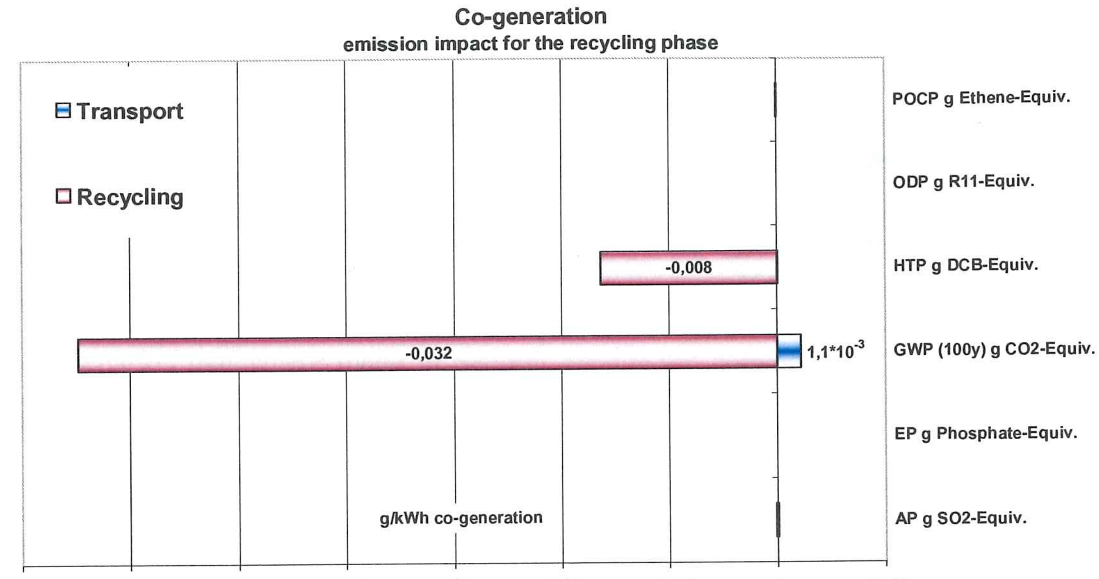


Figure 19. Distribution of eco-points for the operational phase, electricity production. It is clear that the Acidification potential (AP) has the largest impact.

7.1.3 Recycling phase

Emissions from transport of material and recycling of the metals for selected impact categories are shown in Figure 20. The positive effect of recycling the metals is dominant. The impact of transportation of metals to Europe for recycling shown in blue is low compared to the positive effect of recycling which is shown in red and in negative numbers. The recycling phase has a positive impact on the selected emission categories, especially global warming.



	AP g SO2-Equiv.	EP g Phosphate-Equiv.	GWP (100y) g CO2-Equiv.	HTP g DCB-Equiv.	ODP g R11-Equiv.	POCP g Ethene-Equiv.
☐ Recycling	-6,40922E-05	-1,16124E-05	-0,032392467	-0,008142156	-1,11215E-09	-1,91602E-05
⊟ Transport	1,05848E-05	1,96497E-06	0,001086087	2,42643E-05	3,86888E-10	1,65752E-06

Figure 20. Emission impact of the two processes for the recycling phase. The figures below the figure are in grams of equivalents per kWh of co-generating production. There is a benefit of recycling the metals, especially due to the reduction of the release of carbon dioxide. Negative values indicate positive environmental effects.

In Table 7 the emissions of selected impact categories for the recycling phase are listed.

Table 7. Emissions connected to the selected impact categories for the recycling phase (CML2001) (50 years).

Impact category	Co-generation with transport pipe (g / kWh)	Electricity production (g / kWh)
Acidification Potential (AP) SO_2 equivalent	-5,35*10-5	-1,47*10-4
Eutrophication Potential (EP) phosphate equivalent	-9,65*10-6	-2,64*10-5
Global Warming Potential (GWP 100 years) CO_2 equivalent	-0,031	-0,086
Human Toxicity Potential (HTP) DCB equivalent	-0,0081	-0,022
Ozone Layer Depletion Potential (ODP) R11 equivalent	-7,25*10-10	-1,99*10-9
Photochem. Ozone Creation Potential (POCP) ethane equivalent	-1,76*10-5	-4,7*10-5

7.2 Comparison with other energy systems

The main impact categories Acidification potential (SO_2 equivalents) and Global Warming Potential (CO_2 equivalents) are here compared to emissions from other energy productions, both fossil fuels and renewable sources. The basis for the comparison is electrical energy production, but the emissions concerning co-generation from Nesjavellir are also included in the figures. The emissions of NO_x gases are also included, however emissions data for NO_x from the ENEL geothermal power plant at Bagnore3 was not available.

The data for the emission from the hydro power plant is from Statkraft in Norway, as described in Environmental Product Declaration (EPD) for the Trollheim kraftverk (Statkraft, 2002). Data for the wind energy production is from Vattenfall AB, Sweden, an EPD for their wind-power parks in Sweden (Vattenfall, 2003). Also an EPD of an electricity generating geothermal power plant has been done in Italy, of ENELs, Bagnore3 geothermal power plant in S.Fiora, Grosseto in Italy (ENEL, 2006). The data for the fossil fuel energy production is described in a technical report from Paul Sherer Institut (Dones et al., 2006) and also from the Environmental Protection Agency in the United States (EPA, 2006). The data for Nesjavellir are from the two main scenarios for electricity and for co-generation.

In Figure 21 the emission of carbon dioxide equivalents, CO_{2EQ}, is shown for different energy sources. It is clear that the emissions of green house gases from Nesjavellir power plant are low, compared to energy from fossil fuels. Carbon dioxide emissions from fossil energy productions are significantly higher than energy production from renewable sources. However there can be a large difference between fossil power plants there are variations in raw material quality and some have better efficiency and better cleaning technology. The high value of carbon dioxide from the geothermal power plant in Bagnore3 compared to Nesjavellir is mostly due to different geological circumstances.

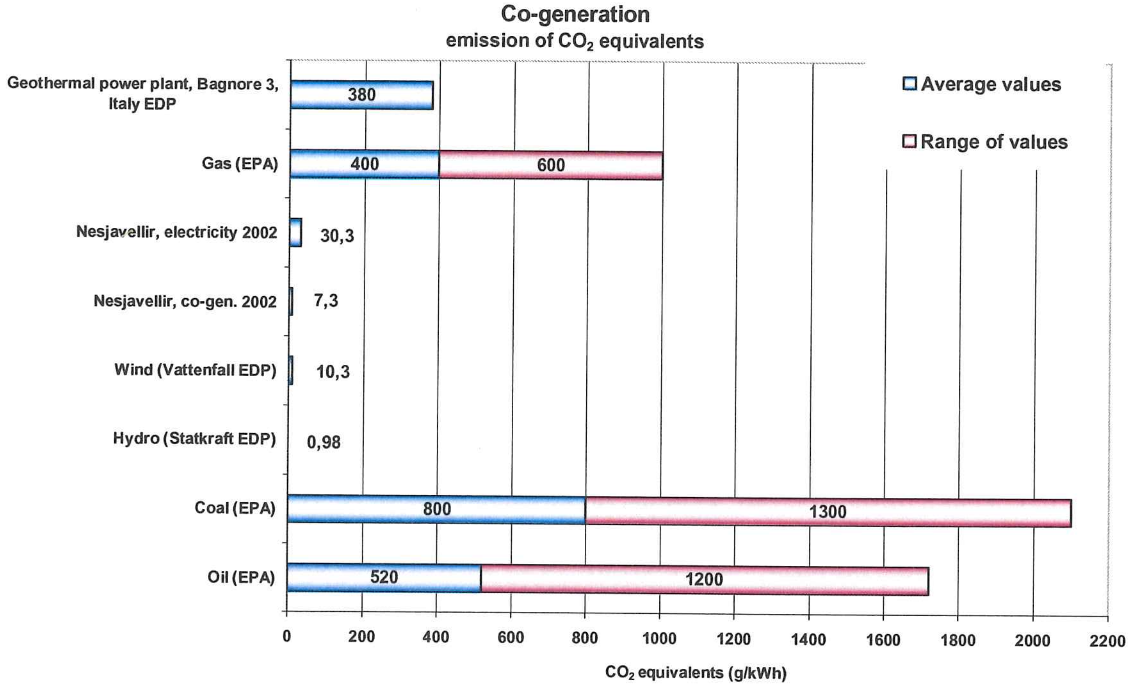


Figure 21. Carbon dioxide equivalents from different electrical energy sources and for Nesjavellir co-generation (electricity and heat). The green house gas emission from Nesjavellir is small compared to electricity production from fossil fuels.

In Figure 22 the emission of sulphur dioxide and sulphur dioxide equivalents from different energy productions is shown. It was not possible to collect data on the sulphur dioxide equivalents from all the different sources. The emissions of sulphur from the fossil energy sources are mainly in the form of SO_2 but in the case of geothermal energy the emissions of SO_2 equivalents are in the form of hydrogen sulphide. In figure 22, three scenarios for the conversion of hydrogen sulphide to sulphur dioxide are shown; 100%, 50%, 25% and 5 % for Nesjavellir. The 100% conversion for hydrogen sulphide to sulphur dioxide is used in the eco-indicator method and the CML2001 method for the calculations of the acidification potential. The conversion rate of hydrogen sulphide is of vital importance in the evaluations of the environmental effects from the Nesjavellir power plant. In Italy the hydrogen sulphide is removed from the geothermal steam, which explains the almost none existing emission of sulphide from the Geothermal power plant in Italy.

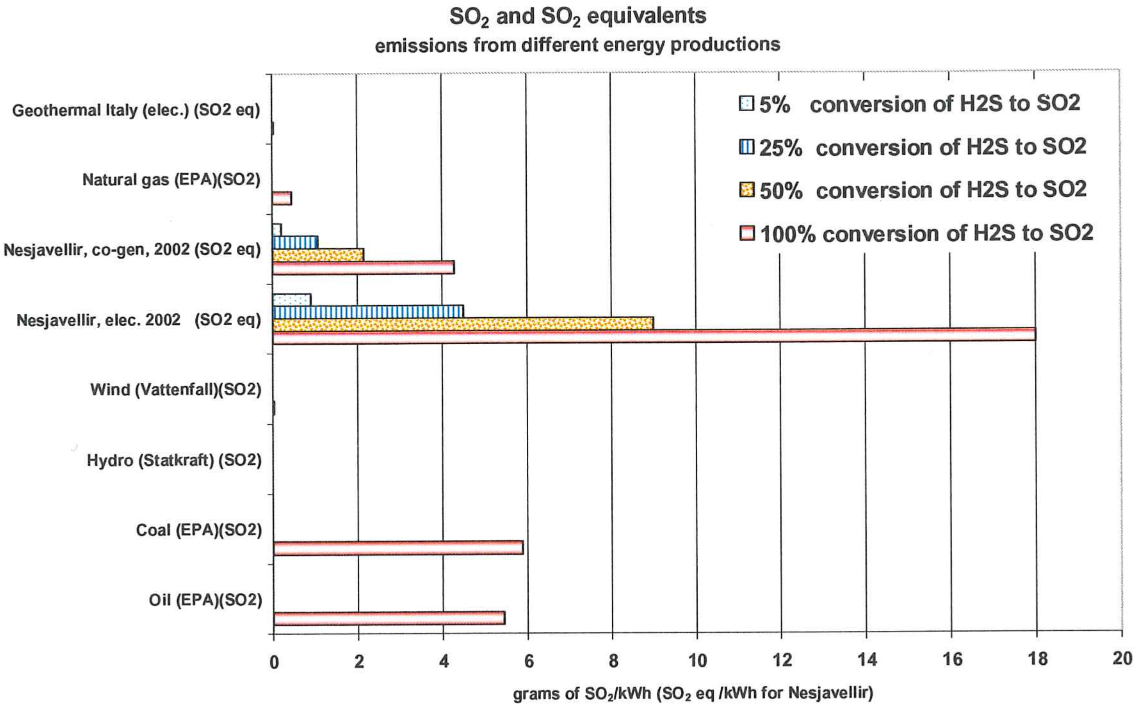


Figure 22. Emissions of sulphur dioxide and sulphur dioxide equivalents from different energy productions in grams/kWh. Conversion of hydrogen sulphide: 100%, 50% and 25% for Nesjavellir.

Emission of nitrogen oxides from different energy sources is shown in Figure 23. Figure 23 shows that the emission of nitrogen oxides from Nesjavellir is very small compared to fossil fuel energy sources.

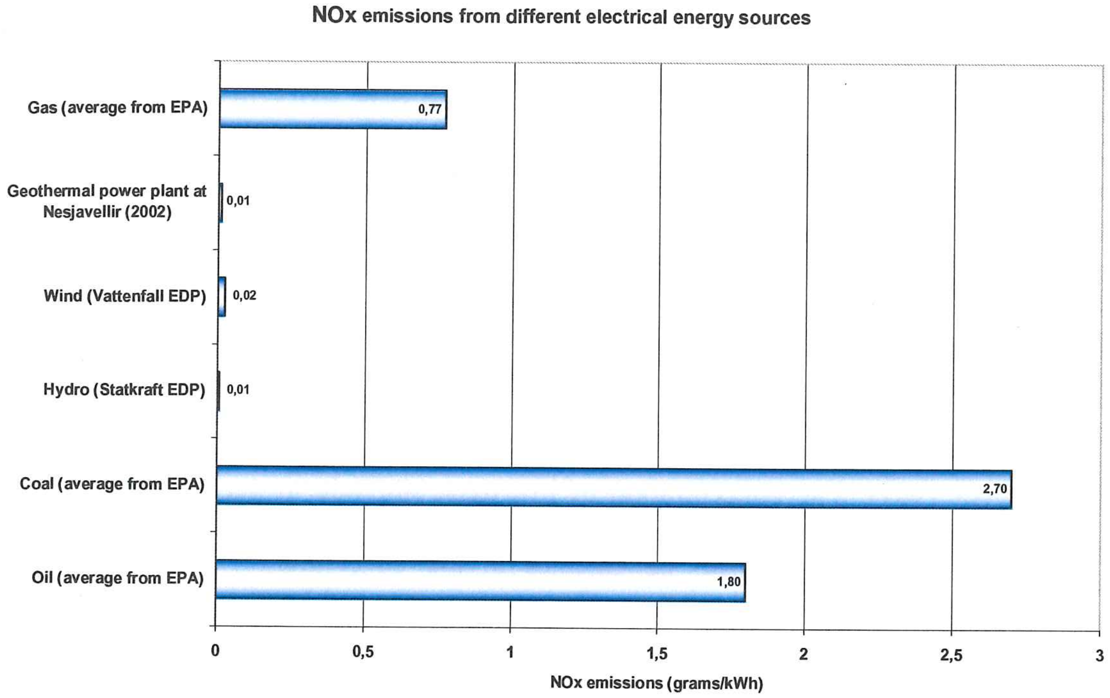


Figure 23. Emission of nitrogen oxides from different electrical energy sources.

7.3 Hydrogen sulphide emissions, discussion on fate and conversion

The results show that the environmental impact from Nesjavellir co-generating power plant is mainly due to the emission of the gases hydrogen sulphide (H_2S) and carbon (CO_2) dioxide from the geothermal steam. In Europe, the environmental impact of hydrogen sulphide (H_2S) is often measured in sulphur dioxide equivalents, (SO_2 eq). Emission that is measured as sulphur dioxide equivalent falls into the environmental impact category, acidification potential (AP). In the Gabi4 program used in the analysis, emission of hydrogen sulphide is expected to convert 100% into sulphur dioxide, when the acidification potential is estimated. How the acidification potential is compared to other environmental effects is different for different tools for environmental analysis. In the results presented in this work, the focus was on the mass of equivalents and on the method of environmental analysis of the eco-indicator 95. The conversion rate of hydrogen sulphide to sulphur dioxide is however not necessarily the same in Iceland as it is in Europe. Especially since the atmospheric conditions in Iceland are different from those in central Europe. Some research has been done in this field that supports the hypothesis that the conversion rate of hydrogen sulphide to sulphur dioxide in Iceland is considerably less than in Europe, but further research is recommended, as discussed in the following section.

Even though the conversion and fate of hydrogen sulphide emissions in Iceland is not fully known, the environmental impact of hydrogen sulphide emissions as analyzed with the program Gabi4 is presented in this report, but these results need to be taken with precautions until the exact conversion rate is known for hydrogen sulphide.

The environmental impact of hydrogen sulphide is calculated in this report as it is analyzed within Gabi4. In this report the 100 % conversion rate of H2S to SO2 is used, as suggested and performed within the program Gabi 4. This has the limitations of unknown conversion rate in Iceland.

7.3.1 The chemical compound: Hydrogen sulphide

Hydrogen sulphide is produced in the anaerobic reduction of sulphate by micro-organisms and is evolved as a gaseous pollutant from geothermal waters (Manahan, 1991). Hydrogen sulphide is a colourless gas and toxic in moderate concentrations (Kristmannsdóttir et al., 2003). Presence of hydrogen sulphide in air is easily detectible by its characteristic rotten egg odour. Allowable concentration of hydrogen sulphide in the air where people are working eight hours a day is 10 ppm (Matthíasdóttir, 2006). Most of the global emission of hydrogen sulphide today is non-anthropogenic from volcanoes (Manahan 1991). The concentration of hydrogen sulphide in geothermal steam can be very different between geothermal sites. Volcanic eruptions can affect the concentration dramatically. There can also be changes in the concentration over time. Hydrogen sulphide is a heavy gas and tends to concentrate in pits and lows, so careful monitoring is needed to ensure that hazardous conditions do not develop locally at geothermal utilization sites (Kristmannsdóttir et al., 2003).

7.3.2 Conversion of hydrogen sulphide to sulphur dioxide

Hydrogen sulphide is expected to convert into sulphur dioxide and sulphates in the atmosphere (Manahan 1991). This conversion is due to photo-oxidization, which is dependent on the atmospheric and weather conditions. The conversion is expected to follow the general process:

$$2H_2S + 3O_2 \rightarrow 2SO_2 + 2H_2O$$

The conversion of hydrogen sulphide to sulphur dioxide is complex, because the sulphur chemistry is complicated and depends on many different factors.

In the years 1994 to 1996 (Kristmannsdóttir et al., 2000) made long-term measurements of the concentration of hydrogen sulphide and sulphur dioxide at all the high temperature geothermal utilization sites in Iceland. The results from these experiments show that the concentration is strongly dependent on weather variables, especially wind and precipitation. Sunshine and temperature also affect the conversion rate. The mean precipitation of H_2S at Nesjavellir was 13 μm and the mean precipitation of SO_2 was 1.7 μm. In Reykjavik the mean precipitation of sulphur dioxide was 1.6 μm. The results from these measurements indicate a small or at least very slow conversion of hydrogen sulphide into sulphur dioxide for the atmospheric conditions in Iceland. In Iceland, it is then possible that the hydrogen sulphide, which is highly soluble in water, will be washed out when it is raining and precipitated as elemental sulphur. However, the modelling does not give very conclusive results due to lack of measurements and other uncertainties. Thus it is, as already mentioned, necessary to study this conversion rate in Icelandic atmospheric circumstances. According to measurements of concentrations of sulphide in rain water at Nesjavellir in the years 1993 through 1995, it was estimated that around 35 tones/km^2/year of sulphide was precipitating in the Nesjavellir area (Ívarsson, 1996). Recently a new Geothermal power plant has started operation in Hengill and the amount of H2S and SO2 is now measured at Grensás in Reykjavík. According to Ármannsson et al. (2001), research scientist at ISOR(Icelandic GeoSurvey) and one of the persons that performed the measurements in 1994-1996, the conversion factor of hydrogen sulphide to sulphur dioxide is maximum 10% in Iceland.

7.3.3 Sulphur dioxide and acidification potential

Acidification originates from emissions of sulphur dioxide and nitrogen oxides. These oxides can react with water vapour and form acids which subsequently precipitate in the form of rain or snow, or as dry depositions. Acidification potential translates the amount of emission of substances into a common measure to compare their contributions to the capacity to release hydrogen ions (ABB, 2001). Sulphur dioxide, SO_2 enters the global atmosphere mainly through human activities such as the combustion of coal and residual oil. The environmental impact of sulphur dioxide emissions is according to the U.S Environmental Protection Agency (EPA, 2006) as follows:

Sulphur dioxide contributes to:

- Respiratory illness, particularly in children and the elderly, and aggravates
- Existing heart and lung diseases.
- The formation of acid rain, which:
  - -damages trees, crops, historic buildings, and monuments; and
  - -makes soil, lakes, and streams acidic
- The formation of atmospheric particles that cause visibility impairment, most noticeably in national parks

The acidification potential (AP) from different substances is specified in table 11 as SO_2 Equivalent.

The acidification potential is calculated according to the equation:

$$AP = \frac{\sum_i V_i / M_i}{(V_{SO2} / M_{SO2})}$$

V_i is potential of H+ equivalence per mass unit of the substance I, M_i is molecular weight of the substance i, and V_{SO2} and M_{SO2} are the subsequent values for SO_2. In table 10 all compounds that contribute to the acidification potential and subsequent conversion factor in Gabi4 are listed (PE-Europe, 2006). The total contribution of acidification is determined by the total of the individual emission and the acidification potential depending on SO_2 (PE-Europe, 2006).

From table 8 it is clear that it is expected that the conversion rate of hydrogen sulphide to sulphur dioxide is 1.88, which implies 100% conversion. The molar mass of hydrogen sulphide is 34 and of sulphur dioxide 64.

Table 8. Related SO_2 equivalents from emissions of selected substances (from Gabi4).

Substance	SO_2 - equivalent
Nirtic acid	0,508
Chloromethane	0,634
Sulphuric acid	0,653
Nitrogen oxide	0,7
Trichloroethane	0,72
Trichloroethane (1.1.1 trichloroethane)	0,72
Dichloromethane	0,744
Ammonium nitrate	0,8
Trichloroethane (chloroform)	0,803
Trichlorocarbon (tertra chloromethane)	0,83
Hydrochloric acid	0,88
Sulphur dioxide	1
Prussic acid	1,185
Fluoro hydrogen	1,6
Hydrogen sulphide	1,88
Ammonia	1,88

Removal of hydrogen sulphide in Iceland and Italy

Kristín Vala Matthíasdóttir wrote her M.Sc. thesis in chemical engineering on the removal of hydrogen sulphide from non-condensable geothermal gas at Nesjavellir power plant in 2006. The main results of her thesis is that a process called Fe-Cl hybrid process has the lowest start-up cost and is the only process that generates profit. In Italy the hydrogen sulphide is cleaned out of the geothermal steam. ENEL, a power company in Italy and Europe, has developed and patented an abatement technology named "AMIS" specifically designed to remove the hydrogen sulphide and mercury from geothermal emissions. This technology is successfully installed in many Italian geothermal power plants. (Malloggi et al., 2007)

7.3.4 Research questions on conversion and fate of hydrogen sulphide

Ongoing research 2006-2007:

There are many ongoing research projects on the topic of hydrogen sulphide in Iceland. A short description of some of the main projects follows. At the University of Iceland, Snjólaug Ólafsdóttir has finalized her masters degree where she has looked at the concentration of hydrogen sulphide and sulphur dioxide in Reykjavik and possible changes due to the opening of the new geothermal power plant at Hellisheidi. At the University of Akureyri (UNAK) there is an ongoing research on protein (biomass) production from bacteria which can possibly thrive on the emissions in geothermal steam, especially the hydrogen sulphide and carbon dioxide. Dagný Björk Reynisdóttir finalized her M.Sc. degree at UNAK, looking into that possibility. At ISOR there are many ongoing research projects regarding geothermal energy utilization and geothermal fields. An interesting research on the changes in the natural flow of hydrogen sulphide before and after geothermal utilization at specific sites is studied. This research is ongoing at

ISOR. A company called Prokatin is doing interesting experiments on the possibility of removing the hydrogen sulphide from the steam in Nesjavallavirkjun. Orkuveita Reykjavikur is working on a project that makes a three dimensional graphical overview of the distribution of hydrogen sulphide in a certain radius around one of their geothermal power plants.

Suggested research questions:

The environmental impact of emissions of hydrogen sulphide on Icelandic soil, vegetation and other organisms is practically unknown. Around Nesjavellir, there are no obvious signs of damaged vegetations. Will the emission of hydrogen sulphide affect Icelandic vegetation and fresh water in the long run? If so, then how? How far from the power plant can the emission be detected? Further research on how atmospheric conditions in Iceland affect the conversion of hydrogen sulphide to sulphur dioxide is needed. It is of importance to know the actual fate of H_2S and its conversion rate in Iceland? Is it: 1%, 10%, 50% or 100%? Can the increase in the utilization of geothermal energy in Iceland have negative effect on vegetation or fresh water in Iceland? The Icelandic soil and vegetations is different from the soil and vegetation in central Europe – is the Icelandic vegetation more resistant to hydrogen sulphide or possible sulphur dioxide exposure? How much hydrogen sulphide is submitted naturally from geothermal fields in Iceland, compared to the flow from geothermal utilization? The flow from geothermal utilization will be approximately 33.000 tones per year after planned extension (Matthíasdóttir 2006).

7.4 Discussion on changes in the carbon dioxide emission

Emissions of green house gases from geothermal energy production in Italy are not considered to add to the natural flow of greenhouse gases from a geothermal field. Studies performed in Italy, confirm this assumption (Ármannson et al., 2001). The government of Iceland decided in 2001 that greenhouse gas emissions from geothermal power utilization should not be included in the total greenhouse gas emissions inventory in Iceland. This decision is under re-evaluation at the ministry of environment, mainly due to new research results in this field carried out by Halldór Ármannsson and Þráinn Friðriksson at ÍSOR (Ólafsson, 2006). Their research considers the changes in natural emissions of carbon dioxide in the utilization areas versus the emissions from the power plant. Result from Reykjanes in Iceland show that the natural CO_2 emissions under low-production conditions are about 16% of the expected emissions from a 100 MW power plant, which has recently been launched at Reykjanes. (Friðriksson et al., 2006)

Long-term utilization of geothermal reservoirs may lead to a decrease in the concentration of CO_2 in the steam. It has been observed in Italy that there was a decrease in concentration of carbon dioxide in the geothermal steam at some sites and this seems to be the case at Nesjavellir also. This decrease can be caused by recharge of cooler water into the producing aquifers (Giroud et al., 2005). Changes in concentration of carbon dioxide in the geothermal steam from Nesjavellir, over a nine year period, is plotted in Figure 24. There has been a reduction in the concentration of carbon dioxide over this time from around 3.700 mg/kg to around 2.200 mg/kg. Data for this LCA was gathered from the operating year 2002. It is difficult to say how this reduction will be in the future, wether it will continue to decrease or if it will increase again or stabilize. Since the results from this LCA show that one of the main contributors to the overall environmental impact is the emission of carbon dioxide from the geothermal steam, any reduction in the concentration of carbon dioxide influences the results significantly. It is however impossible to predict how the concentration will change.

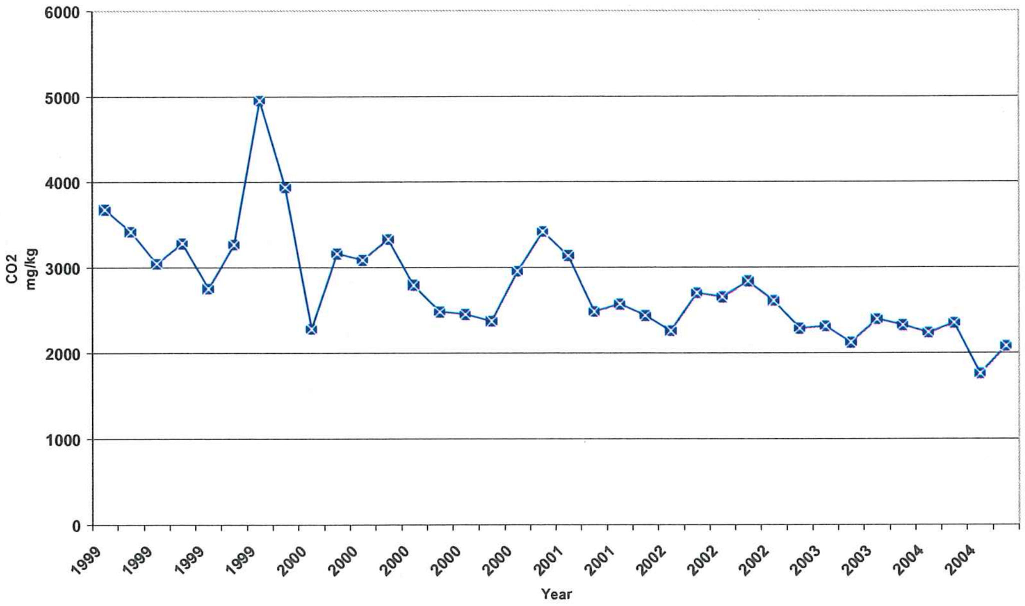


Figure 24. Changes in the concentration of carbon dioxide, over time, in the geothermal steam at Nesjavellir.

A log linear model of possible future concentration changes of CO_2 in the geothermal steam is shown in Figure 25. Since the future concentration of carbon dioxide in the steam is uncertain, the results for this LCA are presented using a constant CO_2 value from the year 2002. This change in concentration is interesting and should be closely monitored.

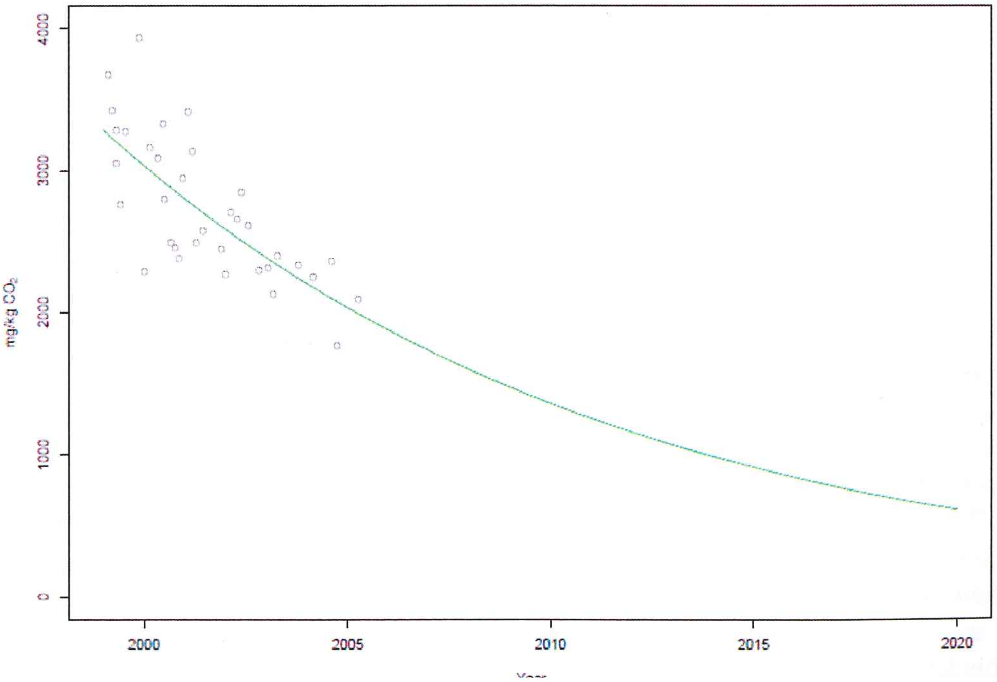


Figure 25. Log-linear model of changes in carbon dioxide emissions in geothermal steam from

Nesjavellir.

Orkuveita Reykjavikur plants each year thousands of trees. In the year 2002, 25,624 trees were planted. These trees can capture about 48 tones of carbon dioxide or around 0.3 % of total carbon dioxide emissions per year. Cumulative carbon dioxide capture, from previous planting years, is expected to amount to around 1.200 tones, around 8% of total carbon dioxide emissions in the year 2002 (Orkuveita Reykjavíkur, 2004).

There has been an increasing interest in technologies that can capture the carbon dioxide from the emissions from fossil power plant. There has been great progress in this field and this could be an interesting possibility for future utilization of geothermal power. Orkuveita Reykjavikur is participating in the Carb-Fix project which purpose is to develop methods to safely store CO_2 as solid calcium carbonate in basaltic rock (Orkuveita Reykjavíkur, 2007)

8 Discussion and conclusions

The main conclusion of the LCA study is that the overall environmental impact of producing electricity at the Nesjavellir power plant is mainly from the operational phase of the power plant. This is due to the emission of hydrogen sulphide and carbon dioxide from the geothermal steam. The environmental impact of these gases is measured in acidification potential and global warming potential. The actual values for these emissions for the electrical production, 18,1 g/kWh $SO_{2(Eq)}$ (Acidification potential) and 30,3 g/kWh of $CO_{2(Eq)}$ (Global warming potential) and for the cogeneration 4,29 g/kWh $SO_{2(Eq)}$ and 7,29 g/kWh of $CO_{2(Eq)}$. The LCA results are therefore very dependent on the concentration of these gases. Since the concentration of these gases can be different from one time to another and from different holes and areas, it is difficult to make an exact analysis of the environmental effect per kWh. This concentration difference was shown in Figure 9 and 22. According to the eco-indicator the most significant environmental effect is the emission of hydrogen sulphide. In the eco-indicator and the CML2001 method it is estimated that hydrogen sulphide converts 100% into sulphur dioxide. This makes the results tentative since studies performed in Iceland have shown that the conversion factor of hydrogen sulphide to sulphur dioxide is could be far from a 100% under the Icelandic atmospheric conditions. Thus, the conversion of hydrogen sulphide to sulphur dioxide in Iceland is a research topic of great interest. Also, in the future it would be interesting to keep track of how the concentration of carbon dioxide will continue to change in the geothermal steam at Nesjavellir.

Estimated lifetime of the power plant also influences the results as presented in Section 7.1.1. It is impossible to know how long the power plant will be operating; a life time of 50 years is thought to be a reasonable estimate.

Simplifications made for the construction phase are not expected to have significant influence on the main results. Also the estimates in the recycling phase are not likely to influence the overall results significantly.

The effect of the production of metals in the construction phase is also a large contributor to the environmental effects, but he hot water transport pipe to Reykjavik is the most influential part when looking at co-generation. The power house with the turbines and generators is the largest contributor when looking only at electricity production in the construction phase. The main environmental effect is from the production of metals, the global warming potential, is very dependent on which kind of energy is used to produce the metals. These results are not surprising and confirm results from the similar analysis for renewable energy production mentioned from Vattenfall and Statkraft.

The results show that there is a significant environmental benefit in utilizing the waste heat energy from the electrical energy production for thermal energy production.

Possible actions for improvement could be to clean out the hydrogen sulphide and the carbon dioxide by capturing it from the steam for permanent storage or other disposal. Other possibilities are to use metals with best available environmental profile and recycle close to 100% of the metals used.

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Appendix 1

Construction phase

Total emission of selected compounds (electrical and co-generation) from the construction phase

Compound	Co-gen with tranp.pipe (grams/kWh)	Co-gen (grams/kWh)	Electricity (grams/kWh)
CO_2	0.678	0.498	2,0828
CO	0.0053	0.004	0.016
H_2S	8,2E-06	5,5E-06	2,2E-06
NO_x	0,00176	0,0012	0,0052
N_2O	5,3E-06	3,9E-06	1,6E-05
SO_2	0,00223	0,00179	0,00752
NMVOC	0,00038	0,00029	0,0012
CH_4	0,00215	0,001575	0,00655
VOC	2.5E-05	1,8E-05	6,9E-05

Operational phase

Emissions of selected chemical compounds for different life time scenarios for the construction phase.

Compound	Co-gen with transp. pipe		Co-gen		Electricity	
	30 Y	70 Y	30 Y	70 Y	30 Y	70 Y
CO_2	1.13	0.48	0.83	0.356	3.47	1.49
CO	8,88E-03	3,81E-03	6,67E-03	2,86E-03	2,73E-02	1,17E-02
H_2S	1,36E-05	5,82E-06	9,09E-06	3,9E-06	3,80E-05	1,63E-05
NO_x	2,94E-03	1,26E-03	2,07E-03	8,86E-03	8,67E-03	3,71E-03
N_2O	8,88E-06	3,81E-06	6,58E-06	2,82E-06	2,74E-05	1,18E-05
SO_2	3,72E-03	1,59E-03	2,98E-03	1,28E-03	1,249E-02	5,352E-03
NMVOC	6,39E-04	2,74E-04	4,81E-04	2,06E-04	2,01E-03	8,63E-04
CH_4	3,58E-03	1,53E-03	2,61E-03	119E-03	1,092E-02	4,682E-03
VOC	4,23E-05	1,81E-05	3,12E-05	1,34E-05	1,154E-04	4,948E-05