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Factors for Primary Energy Efficiency and CO_2 Emission of Geothermal Power Production

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ABSTRACT

The aim of the study is to produce standardized factors for primary energy efficiency (PEE) and CO_2 emission for geothermal power production. These factors, or energy performance indicators, have been developed for different types of power production methods as a form of comparison on greenhouse gas emissions and how much primary energy is needed per kWh delivered to consumers. The calculation of these factors for geothermal energy utilization has had little attention while factors for many other types of energy conversion technologies have been developed and published during the last years. The focus of this study is to calculate the primary energy (PE) and CO_2 factors for geothermal based power production based on data from the Helisheidi power plant in South-West of Iceland by using methods of life cycle assessment (LCA). The method of LCA provides a holistic approach to evaluate the total impact on environment and on consumption of primary energy and natural resources. Preliminary results on the primary energy factor for Hellisheidi geothermal power plant is found within the minimum/maximum range of 2.7 to 9 kWh primary energy per kWh electricity produced and the CO_2 emission factor is calculated to be in the minimum/maximum range of 35 – 45 kg CO_2 equivalents per produced MWh. More detailed factors need to be calculated with a more extensive life cycle analysis including all processes within the life cycle of the power plant.

1. INTRODUCTION

Primary energy factors (f_p) have been developed as a form of comparison on how much primary energy is needed to deliver 1 kWh produced with different types of power production methods. Another important performance indicator for different energy conversion systems is the CO_2 emission factor, stating how much greenhouse gas emissions in CO_2 equivalent is produced per MWh of electricity or heat generated. The calculation of primary energy and CO_2 emission factors for geothermal power production has had little attention while factors for many other types of energy technologies have been developed during the last years. The importance of these factors is stated mainly in the new recast of Directive 2002/91/EC of the European Parliament and of the Council on the energy performance of buildings (EU, 2003). There it is stated that before the end of year 2010, all new building occupied by public authority should be issued energy performance certificates showing these factors based on the energy mix used by the building and the buildings' energy performance.

Geothermal power plants are situated in 23 countries (2007) and with increasing fossil fuel prices and focus on renewable energy, these power plants producing "green energy" become more viable in various locations around the world. It is thus important to investigate their primary energy efficiency and environmental impact as a comparison with other energy conversion technologies. These energy performance indicators can be used to help with decision making of future developments, policy making and energy rating of buildings.

Countries with access to geothermal areas and produce heat and/or power by geothermal utilization within the European Union (EU) are; Italy, Greece, Germany, Bulgaria, Portugal (Acores), Slovakia and Hungary. Other European countries such as Iceland and Turkey, which are not current member states of the EU, also utilize geothermal energy extensively. Thus, electricity and heat based on geothermal energy are a part of Europe's energy mix. For countries using geothermal based power and/or heat and complying to EU legislation, it is thus important to have easy access to standardized factors accounting for the primary energy efficiency and CO_2 emissions from geothermal based heat and power.

1.1 Energy Performance Indicators for Primary Energy Consumption and CO_2 Emissions

According to the Directive 2002/91/EC of the European Parliament and of the Council of December 16 2002 on the energy performance of buildings, indicators on the energy performance of buildings shall include the consumption of primary energy and the CO_2 emissions resulting from the buildings energy usage. Factors for primary energy consumption and CO_2 emissions have been calculated for various energy chains producing electricity, and values for these factors are given in Annex E of the ISO standard ISO15603 on the energy performance of buildings. An overview of these factors is given in Table 1.

As seen in the standard (ISO15603:2008) and Table 1, no indicators are given for geothermal power. The directive is under reconstruction and a recast has been released, as mentioned before. Thus, there is clearly a need to calculate these factors for all major energy chains producing both electricity and heat, which is delivered to buildings within the European Union and in countries following EU legislation. The calculated factors for geothermal energy utilization should then be included in the standard ISO15603 for easy access for those in need to calculate the energy performance of buildings for the energy performance certificates.

Table 1: Energy performance indicators for various sources of electricity (ISO15603:2008).

Source of electricity	Primary energy factors f_p [MWh primary energy / MWh delivered energy] Non-Renewable	Total	CO_2 production coeff. K [Kg/MWh]
Hydraulic power	0.50	1.10	7
Nuclear power	2.80	2.80	16
Coal power	4.05	4.05	1340
Electricity mix UCPTE	3.14	3.31	617

1.2 Life Cycle Assessment and the Energy Performance Indicators

The Directive 2002/91/EC of the European Parliament and of the Council of 16 December 2002 on the energy performance of buildings defines the concept of primary energy as energy that has not undergone any energy conversion process. The primary energy factor must thus represent all the primary energy consumed in order to provide one unit of heat or power to the consumer. Primary energy consumption of energy chains is not only based on the consumption of fuel or energy source in the power or heat generation process, but also all the primary energy needed for the construction, operation and possibly demolition of the production facilities as well as the primary energy needed for the distribution of the product. To calculate such accumulated primary energy use the method of life cycle assessment is well suitable. LCA is a method that has been developing since the earliest performance of such a study in 1969 and standards on the methodology where issued in the late 1990s (A. Russell, 2005).

LCA has been considered as a good tool to achieve a holistic approach on evaluating the environmental impact of a product. Today, it is widely used to investigate all kinds of product systems and has given valuable insight on the total impact of products and systems on the environment by not only focusing on the operational face itself of the product or the system. Many interesting results have been achieved by using this methodology and those results form a basis for evaluating and comparing different solutions for production of various products, such as vehicles for transport, soft drink containers and power conversion technologies. On the other hand, LCA in the process industry has had much less attention than for manufacturing processes and research is needed before complete methods are readily available for direct application of LCA of processes (Baumann & Tillman, 2004). The application of LCA on geothermal energy utilization can be valuable for LCA developers for further improvement and adjustments on the LCA methodology for the process industry.

Using LCA to calculate the total primary energy consumption and CO_2 emission for power production based on geothermal energy will help identify how significant the construction, collection of geothermal fluid and even demolition phase of the power plant and the distribution system have on the total primary energy consumption of the power production system. It can identify the impact of the drilling of wells, manufacturing of power plant components and piping, construction of buildings and roads associated with the power plant, operation of the power plant itself and the primary energy extracted from the geothermal reservoir and even the impacts of constructing and operating the distribution facilities.

1.3 Regulatory Documents and Standards

The EU directives associated with the concept of primary energy efficiency and the energy performance indicators are mainly (Berner & Ulseth, 2008):

- Directive 2002/91/EC of the European Parliament and of the Council of 16 December 2002 on the energy performance of buildings
- Directive 2004/8/EC of the European Parliament and of the Council of 11 February 2004 on the promotion of cogeneration based on useful heat demand in the internal energy marked and amending directive 92/42/EEC
- A proposal for a new EU directive on the promotion of the use of energy from renewable resources

Standards involved with the calculation of the energy performance indicators are mainly:

- EN 15603 – Energy Performance of buildings – Overall energy use and definition of energy ratings
- Various standards within EN 15316 – Heating systems in buildings

A comprehensive list of standards can be found in the paper by Berner & Ulseth (2008).

1.4 Sustainability Indicators

Another type of indicators for assessing energy conversion system are sustainability indicators. These indicators do not only take into account the environmental impact of different technologies, but also the cost, availability, social impacts and other factors that are not neccesarily an output from a LCA study but LCA is often used as a tool for evaluating these types of indicators. In a review study by Evans, Strezov, & Evans, (2009), the sustainability indicators for various types of renewable energy technologies are compared and there, geothermal energy is rated as the least sustainable energy technology compared to hydro, wind and photovoltaics. This is mainly due to water consumption, CO_2 emissions (in CO_2 equivalents), efficiency, availability and limitations and social impacts. The indicators do not include the primary energy consumption associated with each energy tecnholgy but are closely related to LCA and the concept of energy performance indicators.

2. GEOTHERMAL POWER PRODUCTION AT HELISHEIDI POWER PLANT

Helisheidi Geothermal Plant is situated at Hengill close to Reykjavik, the capital of Iceland. A 90 MW electricity production started in 2006 after several years of construction and research. In 2007, a low pressure turbine was added, increasing the power generation to 120 MW. A year later, another 90 MW were added, making the power generation a total of about 210 MW (213 MW in February 2009). Further developments of the power plant include adding heat production in 2010 for district heating and added power production if possible. Estimated production capacity for the completed Helisheidi Plant is 300 MW electricity and 400 MW thermal energy (Helisheidi Geothermal Plant, 2009).

The plant today is a double flash power plant with high- and low-pressure turbines and separators as seen in Figure 1. The technical complexity is moderate and the plant makes a good basis for an LCA study to evaluate the primary energy efficiency and CO_2 emission of this type of geothermal power plant. Since it in fairly newly constructed, access to detailed background data for the inventory modeling is possible, making the study more reliable and accurate. Environmental assessment for the production is available as well as measurements of various environmental impacts of the power plant, providing data for the impact assessment of the LCA study. When data on the planned heat production becomes available, the plant will also provide a good basis for the life cycle assessment of geothermal combined heat and power plants.

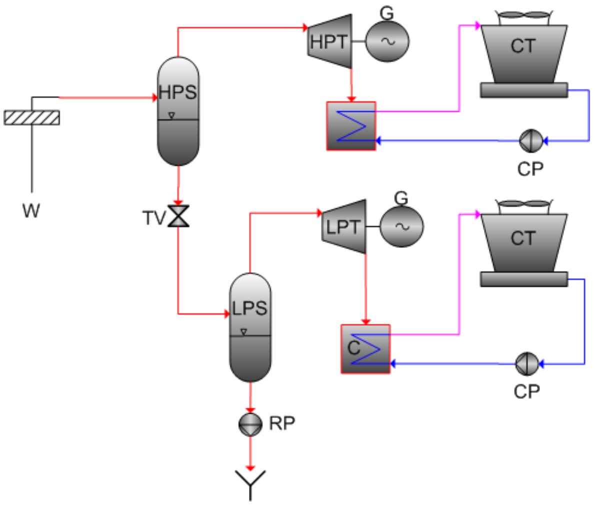

Figure 1: Simplified schematic of the Helisheidi geothermal power plant.

3. LIFE CYCLE ASSESSMENT METHODOLOGY FOR ASSESSING THE HELISHEIDI POWER PLANT

3.1 Goal and Scope of the Study

The main goal of this LCA study is to analyze the two energy performance indicators presenting the primary energy efficiency and the CO_2 emissions for the electricity production at Helisheidi geothermal power plant. The LCA calculations and impact assessment where done by using the LCA software SimaPro 7 (PRéConsultants, SimaPro LCA software, 2009) and using different databases such as the Ecoinvent database (Ecoinvent, 2009) for the inventory information on various raw materials and processes used in the geothermal power plant.

There are numerous geothermal power plants worldwide using similar technology as the Hellisheidi power plant to produce electricity (double flash power plants produced 23% of the electrical power from geothermal resources in 2007, (DiPippo, 2008)) so the results for the energy performance indicators for the power production in Hellisheidi could be used to represent these power plants. Other types of geothermal energy conversion systems, such as single flash and binary systems, should be treated individually when calculating energy performance indicators. Then these results should be compared to the results found for the double flash cycle. Then it is possible to decide whether or not different factors are needed for power produced in different types of geothermal power plants. This will be evaluated in future studies. Another approach could be to gather inventory information from several different geothermal power plants and rely on average data rather than specific data in the LCA modeling. This approach could provide more accurate results since the technology and solutions used to harness geothermal energy is largely dependent on the geothermal area in question, which can require different technical solutions.

The scope of this LCA study includes making the following choices:

- Functional unit
- System boundaries
- Choice of impact categories
- Method for impact assessment
- Data quality requirements

3.2 Functional Unit

The primary energy and CO_2 factors are defined as primary energy usage and CO_2 emission per kWh (or MWh as seen in Table 1) and thus, the functional unit of the study is chosen to be kWh of electricity produced. The functional unit is the reference flow to which all other modeled flows of the system are related.

3.3 System Boundaries

The processes included in this LCA study are mainly the operation and construction of the power plant. The demolition or end-of-life phase is disregarded due to insufficient information at this time. Also, the energy and material flows due to construction and equipment maintenance in the operational phase of the power plant is disregarded but both the demolition and the maintenance will be included in further studies. The time horizon in this study is chosen to be 30 years technical lifetime of the power plant capital goods.

A flow model of the power plant as modeled in the LCA study is shown in Figure 2. The output of the system is 1 kWh of electricity produced in the Helisheidi geothermal power plant. The main material and energy inputs into the energy conversion system are the geothermal power plant unit and the geothermal fluid. The geothermal power plant is constructed from the power plant structures and equipment while the geofluid is transported in collection pipelines from geothermal wells that need to be drilled for the production of the geofluid. Inventory data on all these different components in the flow model was collected and used for the LCA study of the Helisheidi geothermal power plant.

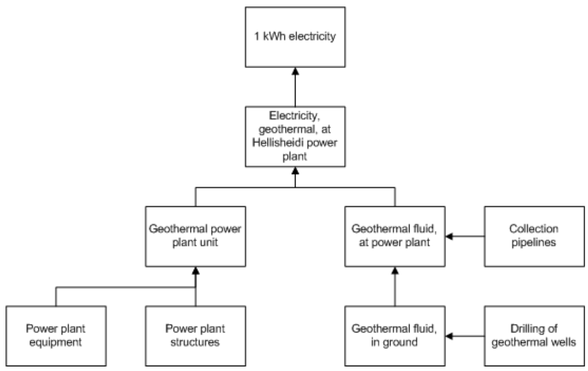

Figure 2: Flow model of the Hellisheidi geothermal power plant

3.4 Impact Categories and Methods for Impact Assessment.

To calculate the two energy performance indicators, the two main impact categories to be used are the energy demand in kWh and global warming potential (GWP) given in CO_2 equivalents.

Two different methods of impact assessment had to be used in the impact assessment calculations. For the primary energy factor, the Cumulative energy demand (CED) method (Klöpffer, 1997) was used which is based on a method published by Ecoinvent 1.01 and available in SimaPro 7 impact assessment methods. For the calculation of the CO_2 emission factor, the CML2 baseline 2000 impact assessment method (PRéConsultants, Methods, 2009) was used to get the total global warming potential in CO_2 equivalent for the chosen functional unit of 1 kWh electricity produced.

3.5 Data Quality

To calculate the energy performance indicators by methods of LCA, reliable inventory information is needed on material and energy flows to and from the geothermal power production facilities during the construction, operation and demolition phases of the lifetime of the facilities. The inventory in this study is constructed from data provided by the power company in ownership of the Helisheidi geothermal power plant (Reykjavik Energy). The data on the construction phase is retrieved from the conditions and specifications for a tender for the construction of the power plant where quantitative information is collected on all major material flows required for the constructions and machinery. The inventory information for the fluid collection and drilling is retrieved from a report done by Reykjavik Energy, including the power and performance of the geothermal wells drilled for the power production (Gunnlaugsson & Oddsdóttir, 2009).

4. IMPACT ASSESSMENT RESULTS FOR THE ENERGY PERFORMANCE INDICATORS

The results from the impact assessment for both primary energy use and CO_2 emissions in CO_2 equivalents are given in Table 2. These are preliminary results achieved from the analysis of the inventory described in Section 3.3. More detailed results can be achieved by adding inventory information on material and energy flows due to maintenance, transport of building materials to the construction site, construction of roads, land use and other processes not included in this study.

The results in Table 2 show four different results for the primary energy factor, f_p, and the CO_2 production coefficient, K, based on different definitions of the energy input from the geothermal fluid into the energy conversion system. The four different definitions are:

- Energy input of geothermal fluid based on enthalpy
- Energy input of geothermal fluid based on enthalpy with subtracted energy content in re-injected fluid
- Energy input of geothermal fluid based on exergy according to a dead state temperature of 15°C
- Energy input of geothermal fluid based on exergy with subtracted exergy content in re-injected fluid according to a dead state temperature of 15°C

As can be seen from Table 2, the values for the primary energy factor vary greatly according to which definition of energy content of the geothermal fluid is used. If the energy content according to the enthalpy of the geothermal fluid is used, which corresponds to the maximum amount of energy input to the system, the total primary energy factor is within the range of 7.5-9 kWh primary energy per kWh electricity produced. If the energy contend is considered to be the exergy of the geothermal fluid according to a specific dead state, in this case with a dead state temperature of 15°C, the primary energy factor decreases dramatically down to 2.7 – 3.5 kWh primary energy per kWh produced electricity. Choosing the exergy as a definition of energy content is debatable but it gives an idea on the minimum amount of energy input per definition to the cycle. The effect of re-injecting the brine from the steam separators causing some of the primary energy to be returned back into the reservoir through re-injection wells leads to a decrease in the primary energy factor since the primary energy content of the re-injected fluid can then be subtracted from the primary energy content of the fluid extracted from the production wells. Since re-injection is performed in the Hellisheidi geothermal power plant, the values with re-injection would be more representative for that specific power plant.

Table 2: Impact assessment results for the energy performance indicators with respect to different definitions on energy content of geothermal fluid (preliminary results).

Source of electricity	Primary energy factors f_p [MWh primary energy / MWh delivered energy] Non-Renewable	Total	CO_2 production coeff. K [Kg/MWh]
Geothermal power, energy	0.1-0.2	8.5-9	35-45
Geothermal power, energy, with reinjection	0.1-0.2	7.5-8	35-45
Geothermal power, exergy	0.1-0.2	3-3.5	35-45
Geothermal power, exergy, with reinjection	0.1-0.2	2.7-3.2	35-45

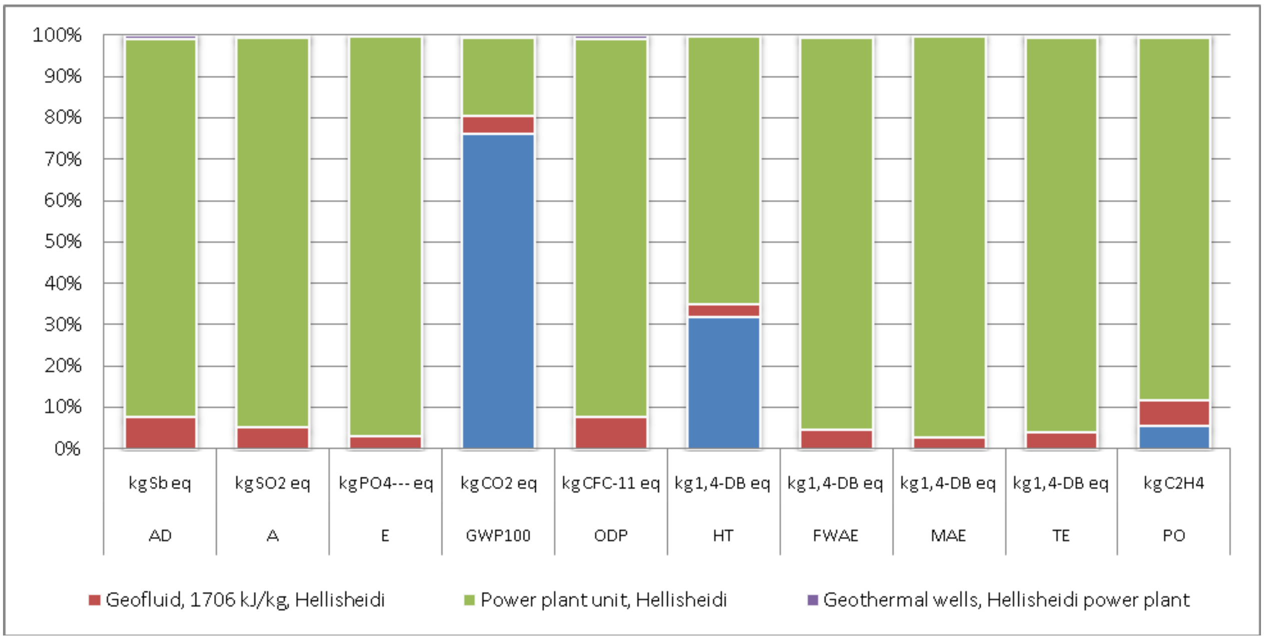

Figure 3: Impact assessment results from the CML2 baseline 2000 method (preliminary results).

The choice between using primary energy factors based on enthalpy or exergy of the geothermal fluid extracted from the reservoir is a subject of debate. No fuel was required to heat up the geothermal fluid as it is heated by the geothermal activity in the earth's crust so some might argue that the renewable part of the primary energy factor for geothermal power could be taken as unity as is done in many cases for other renewable energy sources such as wind, solar and hydro (IEA, 2004). But since geothermal power production is based on the conversion of heat into electricity, the efficiency of such an energy conversion system is low and the waste streams still contain considerable amounts of valuable energy that can be used as a source for other energy carriers such as heat for district heating. This implies that the primary energy input into the cycle should not be considered as unity since valuable waste streams are present after the electricity generation.

It is difficult to compare the values for fp and K from Table 1 and Table 2 due to the fact that a decision has to be made how the energy content of the geothermal fluid for power generation is determined. The lower values for fp where exergy is used as a definition of primary energy content result in the fact that geothermal plants are more primary energy efficient than coal powered plants where the primary energy of the fuel is the heat content of the coal itself. The higher value of fp based on the enthalpy of the geothermal fluid is much higher than the calculated primary energy factor for other primary energy sources and reflects the poor thermal efficiency of geothermal power plants at about 10-12%. The higher value for fp thus makes geothermal power generation less appealing with respect to primary energy efficiency than other power generation methods while the lower fp makes it attractive even though it is considerably higher than for hydro power. This is normal since geothermal power is based on heat conversion but hydropower is produced by converting potential energy into work which is a much more efficient process. It could thus be a political decision on how to assess the primary energy content of geothermal fluid when decisions are made on utilization of geothermal energy.

The non-renewable part of the primary energy factor represents how much primary energy originates from non-renewable energy sources such as nuclear power, coal power or gas power. These energy inputs into the geothermal energy conversion process originate mainly from the construction phase of the power plant, where non-renewable energy sources are used in the production of materials used for construction. The drilling of geothermal wells also requires the use of fossile fuels which contribute to this value. The value for the non-renewable primary energy factor for geothermal power production in Hellisheidi power plant is only a small fraction of the total primary energy input to the system since a vast majority of the primary energy is in the geothermal fluid itself used in the operation of the powerplant.

Results from the CML2 2000 impact assessment gives the result for the global warming potential (GWP100) in kg CO_2 equivalents in addition to results for the following impact categories:

- Abiotic depletion in kg Sb equivalents (AD)
- Acidification potential in kg SO_2 equivalents (A)
- Eutrophication potential in kg PO_4--- equivalents (E)
- Ozone layer depletion in kg CFC-11 equivalents (ODP)
- Human toxicity in kg 1,4-DB equivalents (HT)
- Fresh water aquatic eco-toxicity in kg 1,4-DB equivalents (FWAE)
- Marine aquatic eco-toxicity in kg 1,4-DB equivalents (MAE)
- Terrestrial eco-toxicity in kg 1,4-DB eq (TE)
- Photochemical oxidation in kg C_2H_4 (PO)

The proportional contribution from each process in the geothermal energy conversion system can be seen in **Error! Reference source not found.**. The goal of this analysis was to focus on the global warming potential (GWP100) and the contribution of each process within the system to the GWP can be seen in Figure 4. The global warming potential was calculated to be in the range of 35-45 kg CO_2 equivalents per MWh (35-45 g CO_2 eq per kWh) for the electricity production at Hellisheidi power plant. The geothermal fluid is the largest contributor to the total emissions of greenhouse gases from the energy conversion system while the drilling of the geothermal wells is the second largest contributor. The construction phase including buildings and machinery are responsible for about 4% of the total CO_2 emissions and the collection lines for the geothermal fluid only contributes about 1%. If the CO_2 emission from the power production would only be calculated from the direct emissions during operation of the power plant and not considering the effects of the whole life cycle of the power plant, only about ¾ of the total emissions resulting from the power production would be accounted for. This shows the importance of using methods such as life cycle assessment to evaluate the total environmental impacts of different systems.

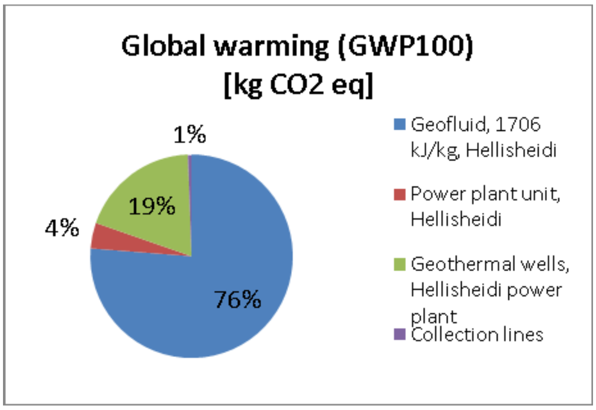

Figure 4: Contribution of the different processes to the total CO_2 emissions.

4.1 Remarks About the Definition of Primary Energy

The primary energy factors for power produced from renewable energy sources such as hydro power, wind energy and solar energy are sometimes calculated by assuming that the primary energy input into the energy conversion system is equal to unity which is the same as assuming that the energy conversion process is 100% efficient. The reason for this assumption is that the primary energy is defined as the first usable stage of the energy flow, which in the case of wind, solar and hydro is the electricity itself produced from these primary sources. (Segers, 2008). For electricity production from heat sources, the first usable stage of the energy stream can be defined as the steam input into the turbine, according to (IEA, 2004). The assumption used for the power production from renewable energy sources tends to underestimate the primary energy input from the original energy sources into the energy conversion system compared to the assumptions made for the heat conversion processes. This will produce biased primary energy factors in favor of the renewable sources.

5. CONCLUSIONS

Energy performance indicators for the primary energy efficiency and CO_2 emissions for the Hellisheidi geothermal power plant can be calculated by methods of life cycle assessment (LCA) which includes all energy and material flows into and from the energy conversion system during the whole lifetime of the power plant. LCA is considered a realistic approach to finding the total impact of products and processes and is well applicable in the calculations of these energy performance indicators. Results from this study show that the primary energy factor for Hellisheidi power plant lies within the range of 2.7 – 9 kWh primary energy per kWh electricity produced in the plant, depending on how the energy content of the geothermal fluid is defined.. The share of non-renewable energy sources within that factor, resulting from the construction phase of the power plant, is only within the range of 0.1-0.2. The energy content of the geothermal fluid itself is the largest contributor to the primary energy input to the system. There is a need for a clear definition on how to calculate the primary energy content of geothermal fluid that takes into account the benefits of geothermal energy being widely considered as a renewable energy source.

The CO_2 emission factor is found to be within the range of 35-45 kg CO_2 equivalents per MWh of electricity produced and the construction phase, especially the drilling phase, contributes 24% of the total emissions during the technical lifetime of 30 years. The methods of life cycle assessment thus contribute to a more accurate estimation of the total emissions of greenhouse gases by taking different life cycle phases into account and not only the operational phase as is widely accepted.

Future studies will include LCA for different types of geothermal energy conversion systems such as for single flash power plants and binary power plants to evaluate the need for different PE and CO_2 emission factors according to which type of technology is used. Also, the impact of producing both heat and power in combined heat and power (CHP) plants on the energy performance indicators will be studied. Further on, factors for direct use of geothermal energy for heat production at low-temperature geothermal areas will be calculated based on the same method developed in this study.

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