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TNO report

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Screening LCA for a geothermal doublet

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Contents

1 Introduction

The aim of this report is to show the results of a screening LCA for a Geothermal doublet installed in the Netherlands in the greenhouse area Het Grootslag Andijk[1].

1.1 What is an LCA?

This section presents the necessary background information on Life Cycle Assessments (LCA) – the methodology used to calculate the environmental impacts. Life Cycle Assessment (LCA) is a method to systematically quantify and compare the effects of a product, system, service or geographical entity. As the name suggests, an important characteristic of LCA is that it takes into account the complete life cycle of a product (cradle-to-grave) from resource extraction to waste treatment, including transport in between. Another important characteristic of LCA is that a wide range of environmental problems can be addressed, such as climate change and toxicity to humans or ecosystems. This way, the trade-off between life cycle stages and/or environmental problem areas is prevented. Finally, LCA is generally considered a comparative rather than an absolute tool. LCA is generally conducted in four interrelated steps: 1) Goal and scope definition; 2) life cycle inventory; 3) impact assessment; 4) interpretation and conclusions (ISO 14040/44).
In the goal and scope definition, where the products to be compared are defined, the functional unit, the type of LCA, system boundaries, and impacts and impact assessment methodology are set. A functional unit is the unit of comparison to which all flows in the inventory are related. It is important that the functional unit is defined in such a way that all systems under comparison fulfill the same function. For the comparison of heating technologies the provision over 1 MJ over X years has been chosen.
Inventory refers to the data gathering phase, where all inputs and outputs of the product system are compiled. These encompass resources extractions as well as emissions into the environment. A widely used European version that is also used in this report is the EcoInvent database (Wernet et al. 2016).
Impact assessment describes the phase, where the long list of interventions is translated into a number of so-called midpoint impact categories by modelling the underlying environmental mechanism. This step allows to add all interventions that contribute to the same environmental problem in one common unit. For instance, emissions of greenhouse gases are re-calculated to kg CO_2-equivalents (CO_2-eq) by using Global Warming Potentials (GWP) that express the contribution of a gas to radiative forcing relative to that of CO_2. For further simplification of interpretation, these midpoint impact categories (often 10 or more) can be translated to endpoints that express the damage these environmental problems cause for Areas of Protections, generally defined as human health, ecosystem health (or biodiversity) and resource availability. The disadvantage of this approach is an increase in uncertainty in the underlying models that link interventions to the endpoints, such as the emissions of CO_2 and reduction in full quality life years due to disease induced by climate change.
A range of impact assessment methodologies is available that translate interventions to midpoints or endpoints. In this report, ReCiPe 2016 (Huijbregts et al., 2016) is

[1] Het Grootslag Andijk, Geothermie Nederland: https://geothermie.nl/index.php/nl/geothermie-aardwarmte/geothermie-in-nederland/projectoverzicht/228-andijk

chosen because it is the most up to date available impact assessment methodology that provides midpoint as well as endpoint indicators in a consistent way. Figure 1 shows the environmental pathways and indictors available in ReCiPe 2016. In this report, first a comparison of for all midpoints is shown (in percentage scaled to the highest impact), then the midpoints are selected that contributed most to the endpoints (shown in absolute numbers per impact category), and in the integrated analysis endpoints are also shown (normalized to the reference: natural gas boiler). For the purpose of this work, the LCA calculations were performed with the commercially available software SimaPro v 9.1 (Simapro, 2020).

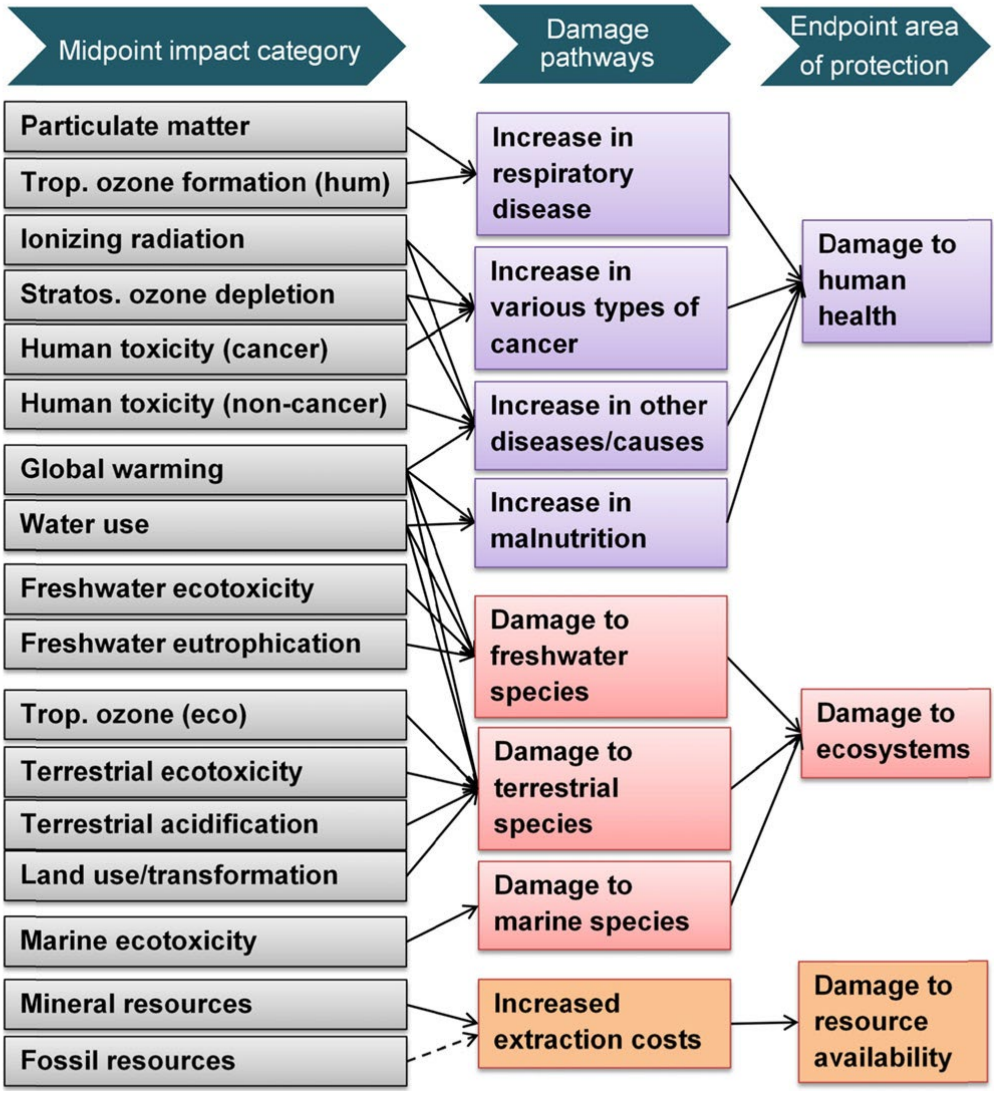

Figure 1: ReCiPe method, source: Huijbregts et al. (2016)

1.2 Geothermal heat installations

In the Netherland, most existing geothermal systems consists of 2 or more borehole wells in an open loop system at a variable depth between 1500-3000 mbgs[2], where hot water from the subsurface (between ~60 and 95 °C) is pumped to the surface by an ESP (Electrical Submersible Pump) to produce thermal energy. A gas/water

[2] Meter below ground surface

separator, particle filters, a heat exchanger, gas dryer, gas boiler and/or CHP are part of the surface equipment necessary to extract the heat from the geothermal source and deliver it into a heat distribution network. Heat pumps can be installed to cool the return temperature of the geothermal water and extract more energy. Figure 2 gives an overview of a general geothermal well schematic.

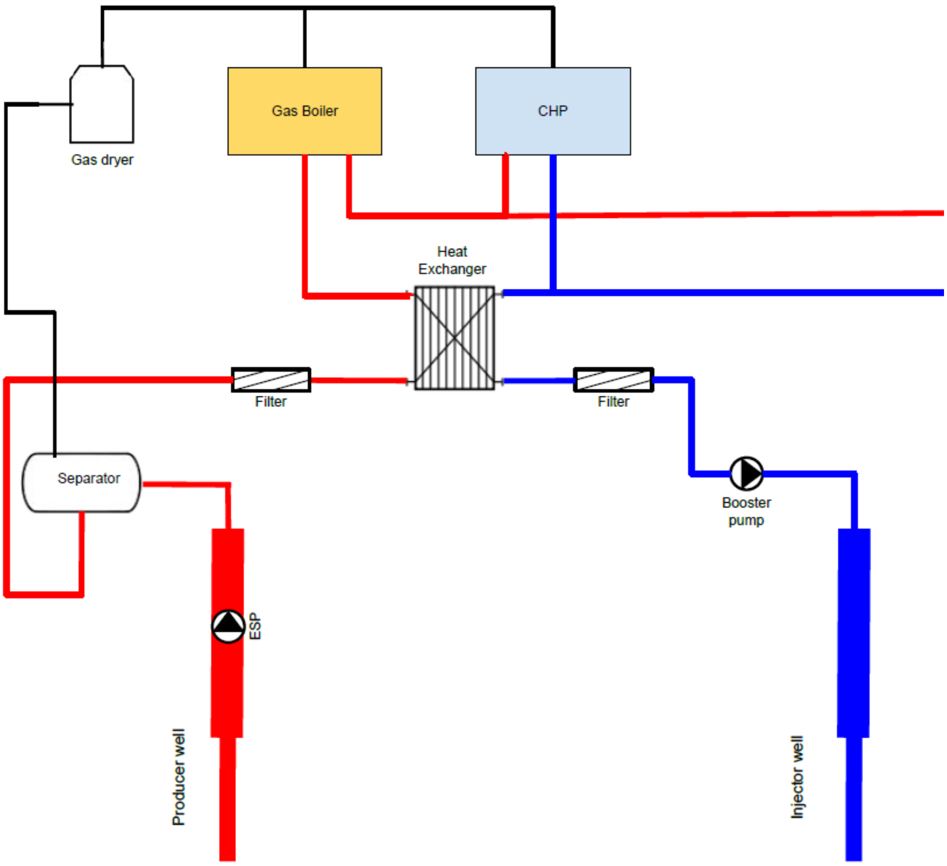

Figure 2: Schematic representation of a geothermal system

Different gasses are dissolved in the geothermal water (e.g. methane, carbon dioxide and nitrogen). Due to the pressure reduction that the geothermal water undergoes when being pumped to the surface, these gasses are released from the water and need to be captured in order to avoid direct emissions to the atmosphere. These gasses are commonly referred to as “formation gasses”. The quality and amount of formation gasses depend on the type of geological formation from where the water is produced.

1.3 Report Structure

The report follows the following structure: chapter two outlines the methodology followed and the assumptions taken at the basis of the calculation, giving an overview of the inventory data and defining the functional unit. Chapter 3 presents the results for endpoint and midpoint impact categories. Chapter 4 shows the comparison with other thermal energy sources and in Chapter 5 the conclusions are presented.

2 Methodology

To carry out the LCA analysis, the commercial software SimaPro v 9.1.1.1 (Simapro, 2020) was used. The method used is the ReCiPe 2016 method.

2.1 System boundaries and functional unit

The system boundaries included the construction, use phase and decommissioning of the geothermal installation, excluding the heat distribution network. The total energy produced by the installation is given by the sum of the heat extracted from the geothermal water and the heat derived from the combustion of the formation gas in an industrial boiler. In the current geothermal installations used for greenhouse heating, often a CHP is installed to produce electricity for the system (ESP's etc) and heat for the greenhouses. The boiler is only used as peak supply. However, in this study it was chosen to burn the formation gas in a boiler and as no data were available on the heat and electricity generated by the CHP. Likely this represents a worst-case scenario, as it will be shown in the following sections, the electricity consumption necessary to operate the installation contributes heavily to the environmental impact.

- Construction:
  - Drilling: Rotary drilling, Diesel consumption: 7 GJ/m, Drilling fluid
  - Steel: Low alloyed or unalloyed steel for pipes
  - Concrete: Portland cement to protect steel pipework
- Use phase:
  - Electricity consumption (This is the total energy used for all the surface equipment and ESPs, as indicated by the system owner)
  - Formation gas leakage (1%) (Methane). This assumption was made based on conversations with EMSA, as it appeared that leakage of formation gasses might not be negligible and lead to important environmental damages. No industry or location data were available for this study.
  - Formation gas combustion in boiler (Boiler efficiency 80%, ideal combustion process)
  - Corrosion inhibitor
  - **Excluded**: Heat Distribution network, separate modelling of surface equipment(CHP, separator, pumps) and maintenance and replacement of equipment
- Decommissioning
  - Gravel and cement to seal the pipes
  - Neglectable energy use assumed

Functional unit: The chosen functional unit is 1MWh of thermal energy produced by means of a geothermal doublet in the Netherlands.

2.2 Inventory

The inventory includes data from the Ecoinvent Database version 3.6 as well as data and parameters relative to the site modelled. The data and parameters relative to the site were gathered from the "Ontwikkelingsplan aardwarmte Andijk, ECW Geo

Andijk”[3] and interviews carried out by the AGS team with the geothermal plant operators. Table 1 gives an overview of the parameters representative for the Andijk installation.
Furthermore, specific data on the type and amounts of steel and concrete used in the reinforcement of the boreholes were calculated based on the End of Well reports design drawings. These data are reported in Table 2.

Table 1: Parameters representative for the geothermal doublet in Andijk

General data		**Unit**
Installed capacity	40	MW
Hours full load (per year)	8760	h
Hours running (per year)	8760	h
Energy production (per year)	350400	MWh/year
Formation gas production	0,4	m3/m3 water
Energy from formation gas	16423,73	MWh/year
Total energy produced	366823,7	MWh/year
Lifetime	35	years
Number of doublets	2	
Number of boreholes	4	
Depth of the well	2000	m
Flow rate (for 2 producer wells)	700	m3/h

Table 2: Amounts and types of steel and cement used in the injector wells

Material	Material specification	Amounts [tons]	Comments
Steel	X70	57,994	Alloyed steel (generally low alloyed steel). For 2 injector wells
	K55	137,473	Carbon steel (unalloyed steel) For 2 injector wells
	L80	434,924	Alloyed steel (generally low alloyed steel) For 2 injector wells
Cement	Class C	312,74	Cement used in de MDM GT 04 project. This well is 2652 m deep. Similar to type III cement.
	Class G	332,36	Cement used in de MDM GT 04 project. This well is 2652 m deep. Clinker with added calcium sulfate or water

2.2.1 *SimaPro modelling*

The energy production of one year was modelled in SimaPro, based on the data reported in Table 1 and Table 2 and complementary Ecoinvent processes. The

[3] Ontwikkelingsplan aardwarmte Andijk, ECW Geo Andijk : https://www.nlog.nl/sites/default/files/2021-01/190718_verzoek_tot_instemming_wp_andijk_publiek_gelakt.pdf

complete overview of the processes used in the LCA modelling software is given in Table 3

Table 3: SimaPro processes used in the screening LCA of the geothermal installation

Phase	**Action/ Material**	**Quantity**[4]	**Unit**	**Comment**	**Ecoinvent Process**
Construction	Borehole drilling	228,57	m	The Ecoinvent process was modified by eliminating the steel and concrete inputs to use the steel and cement data supplied by the plant operators.	Deep well, for geothermal power, onshore, 6000m {GLO}
	Steel	3,31	tons	Proxy for X70 steel	Steel, low-alloyed {GLO}
		7,86	tons	Proxy for K55 steel	Steel, unalloyed {GLO}
		24,85	tons	Proxy for L80 steel	Steel, low-alloyed {GLO}
	Cement	47,39	tons	Proxy for Class C cement	Cement, Portland {Europe without Switzerland}
		50,37	tons	Proxy for Class G cement	Cement, Portland {Europe without Switzerland}
Use Phase	Corrosion inhibitor	66917	kg	Proxy for corrosion inhibitor	Dimethylamine {RER}
	Electricity consumption	$1{,}32 \times 10^7$	kWh		Electricity, medium voltage {NL}
	Formation gas burning	16424	MWh	This process assumes perfect methane combustion in an industrial furnace with an 80% efficiency. CO_2 emissions are modelled according to the formula $CH_4 + 2O_2 = CO_2 + 2H_2O$. The methane used is selected as “input from nature” to avoid the environmental damages associated with natural gas extraction. No methane emissions are assumed	Methane formation gas burned in industrial furnace
	Methane emissions	24528	kg	Formation gas emissions to the atmosphere	Methene

[4] All the quantities have been adjusted per lifetime and to be representative for the geothermal plant in consideration.

				(assuming 1% of the formation gasses escape)	
	Dimethylamine emissions	66917	kg	Emissions of the corrosion inhibitor to groundwater. It is assumed that all the corrosion inhibitor is lost to the environment.	Dimethylamine
Decommissioning	Well closure	229	m	This process only includes cement and gravel to close the well with no energy use.	Deep well closure {GLO}|

3 Results

As mentioned in the introduction, an LCA analysis produces results for Midpoints and Endpoints. While the former are scientifically more accurate, the latter are of easier interpretation as they immediately relate to different areas of protection such as human health, ecosystems and resource depletion. Unfortunately, Midpoints can be difficult to interpret as they are represented by a large variety of indicators (in ReCiPe 16 different indicators) relating to different environmental impacts. One way to prioritize the different midpoint impact categories is to look at the Endpoints and see what midpoint categories contribute most to the endpoints. This is the approach followed in this analysis.

This section will give answers to the following questions:

- What are the life phases of the geothermal installation that most contribute to the environmental impacts?
- What are the impact categories that most contribute to the environmental impacts?
- What are the processes contributing most to each impact category?

Here, the most prominent results are represented in graph form. The SimaPro output is available in the appendices.

3.1 Endpoint analysis

As mentioned in the introduction, the endpoint results relate to three protection areas, namely Human Health (expressed in terms of disability adjusted life years, DALY) ecosystem (expressed in terms of species loss per year, species.yr) and resources (expressed in terms of USD). It is not possible to compare these three categories in an absolute manner and say “what is the most important category” and these represent three different things. Still, it is useful to look at what midpoint categories contribute most to the endpoints, in order to be able to prioritise the different midpoint categories (where the connection between the emissions to the environment and the damage caused is most accurate). Figure 3 shows what midpoint categories are most relevant to the Endpoints, while Figure 4 shows which life phases deliver the largest contribution to the midpoint categories. From these two figures, it can be seen that the largest contributions mostly come from the use phase and partially from the construction phase while the decommissioning phase has no influence so far on the environmental impact.
The most important midpoint categories for human health are:

- Global warming
- Fine particulate matter formation

For ecosystems:

- Global warming
- Terrestrial acidification
- Ozone formation/Land use

For Resources:

- Fossil resources depletion

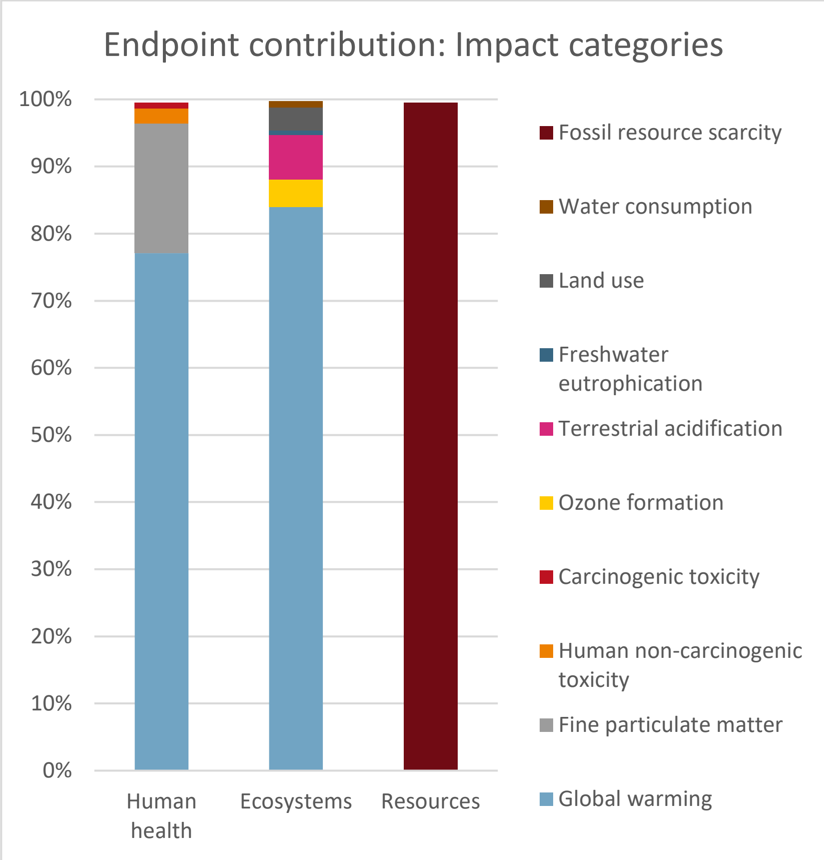

Figure 3: Midpoint categories contributing to the endpoint categories

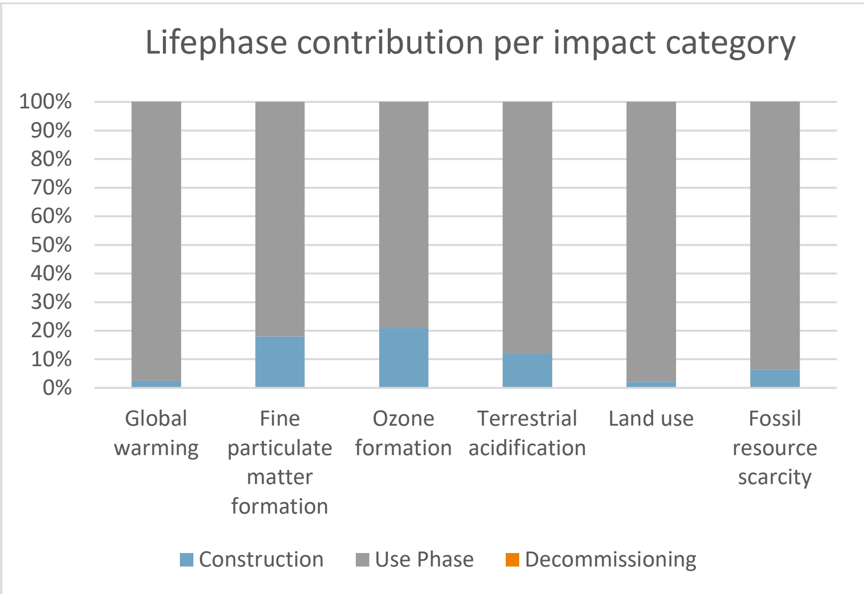

Figure 4: Life phases contributing to the different impact categories.

Table 5 of the appendix shows the endpoints characterised results, and Table 6 to Table 16 show the characterized results for the midpoints that were used to produce Figure 3.

3.2 Processes contribution to the most relevant midpoint categories

The process contribution to the different midpoints can either be determined by looking at the "absolute" contribution of each process to the considered midpoint category or by looking at the network of the process under scrutiny (i.e. a visual representation of all the upstream processes and materials that are inputs for a particular process).
In this analysis, the process network was studied first and then the most impactful upstream processes behind each material/action were highlighted.

3.2.1 Global warming potential (GWP)

The GWP is mostly generated during the use phase (~36 kgCO_2-eq/MWh). While the construction phase generates approximately 0,92 kgCO_2-eq/MWh. These data can be seen in Figure 5.

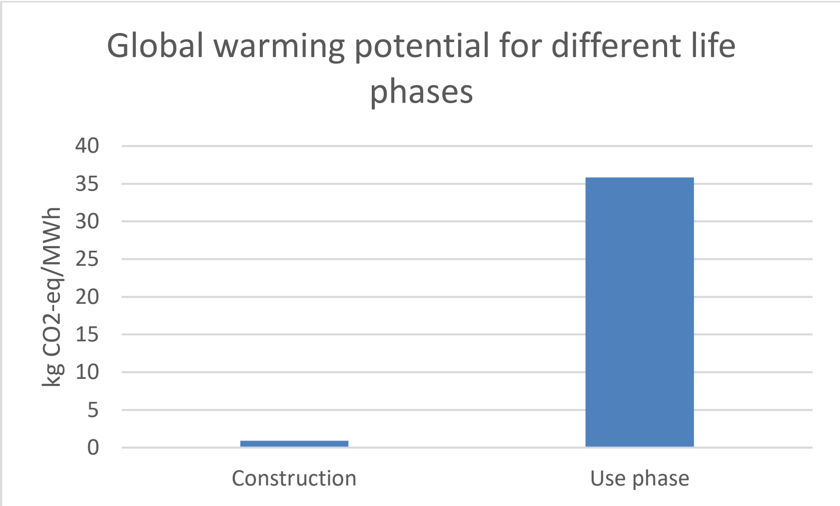

Figure 5: Global warming potential in kg CO2-eq/MWh for different life phases of the geothermal installation

For the use phase, the electricity (necessary to drive the surface equipment and the ESP) contributes approximately 56%, generating ~20 kgCO_2-eq/MWh. This can be seen in Figure 3. It is important to remark that in this case the emissions coming from the formation gas directly (i.e. the formation gas that "escapes" without being burned in the gas boiler) generate 2,27 kgCO_2-eq/MWh. This is approximately 6% of the GWP during the use phase. This is quite remarkable, considering that the underlying assumption is that barely 1% of the formation gas is emitted directly to the atmosphere; for this reason, is advisable to carry out a sensitivity analysis on this point during a follow-up study.

Note!: The assumption that ~ 1% of the formation gas is emitted directly into the atmosphere is considered to high according to experts. This percentage is more likely to be in the order of magnitude of ~0.1%. Therefore it has been decided to remove these emissions ('formation gas emissions') from the final figure in the factsheet.

For the construction phase, most of the CO_2 emissions are generated during the drilling phase (due to the diesel consumption necessary to operate the drilling machines). The processes responsible for the largest contributions of the steel and cement used during the construction phase are the production of pig iron and the production of clinker respectively. The data used to generate the graphs is available in the appendix.

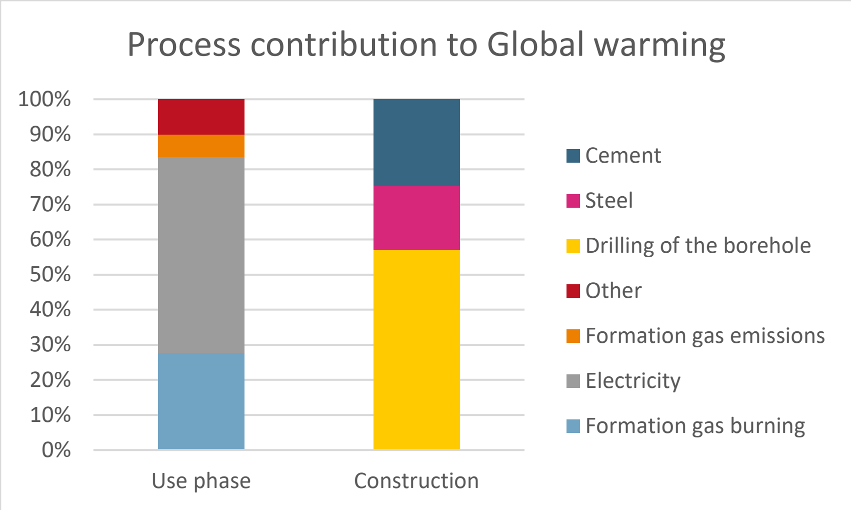

Figure 6: Percentage contribution of different processes to GWP during construction and use phase

In order to check the results obtained in this study, the impacts of the use phase were compared with the results published by the AGS team in the TNO whitepaper "Duurzaamheid van geothermie in warmtenetten"[5]. In this whitepaper, the AGS team analysed the emissions generated by electricity use and combustion of formation gasses during the use phase of a geothermal doublet. The results were expressed in kg CO_2-eq/GJ. This required some adjustment as the functional unit considered in this study is 1 MWh, i.e. 3,6 GJ.

Table 4: Processes contributing to the GWP of the use phase of the geothermal installation (per GJ of produced energy). Comparison of the results obtained in this study and the AGS whitepaper.

	Screening LCA	**AGS report**
	Kg CO_2-eq/GJ	Kg CO_2-eq/GJ
Total	9,96	7,3
Electricity use	5,56	5,1
Methane combustion	2,77	2,2
Methane loss	0,63	n.a.
Others	1,00	n.a.

Looking at the results displayed in Table 4, it can be seen that there is good agreement between the figures obtained in the two studies. The value CO_2 emissions calculated in this screening LCA are higher due to the assumed 1% leakage of formation gasses (0,63 Kg CO_2-eq/GJ) and background processes (e.g. processes related to the electricity grid, transport, etc.) all these processes together contribute 1 Kg CO_2-eq/GJ to the GWP.

[5] https://geothermie.nl/images/bestanden/TNO-2020-duurzaamheid.pdf

3.2.2 *Fine particulate matter formation*

Also in this case, the use phase is the largest contributor to this environmental category, producing ~0,011 kg PM2.5-eq/MWh. The construction phase produces ~0,0025 kg PM2.5-eq/MWh. These data are reported in Figure 7.

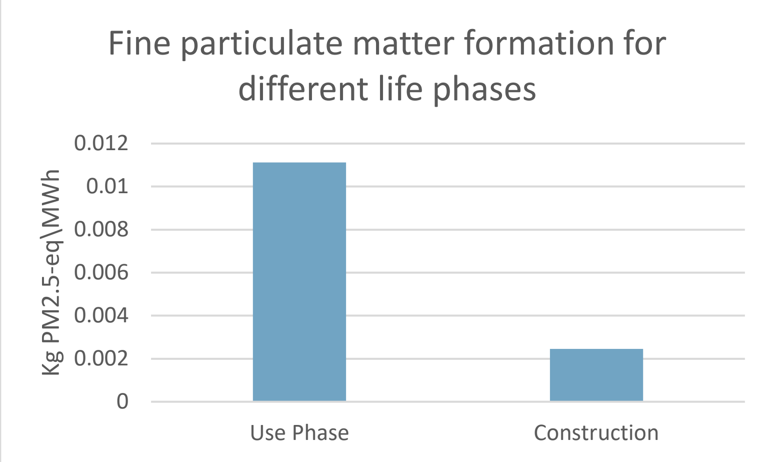

Figure 7: Fine particulate matter formation in kg PM2.5-eq/MWh for different life phases of the geothermal installation

As in the previous case, electricity use is the largest contributor to the Particulate Matter (PM) production (contributing for approximately 96%). The largest contribution comes from the use of coal to generate electricity (as part of the electricity mix). For the case of the construction phase, the diesel consumption necessary to operate the drilling machine is the largest contributor. Again, the processes responsible for the largest contributions of the steel and cement used during the construction phase are the production of pig iron and the production of clinker respectively. As this situation does not change for the following analysed midpoints it is no longer repeated. The data relative to the single process contributions can be seen in the appendix.

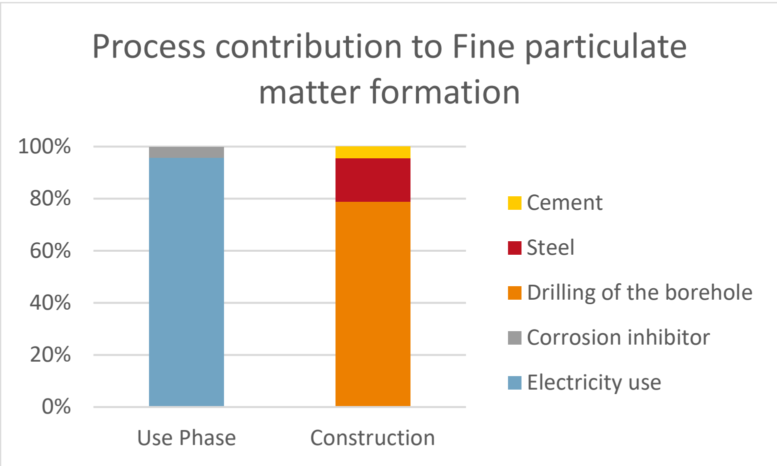

Figure 8: Percentage contribution to fine particulate matter formation during construction and use phase

3.2.3 *Terrestrial Acidification*

As in the previous cases, the use phase is the largest contributor to this impact category, generating 0,033 kgSO_2-eq/MWh in comparison with 0,0045 kgSO_2-eq/MWh generated by the construction phase.

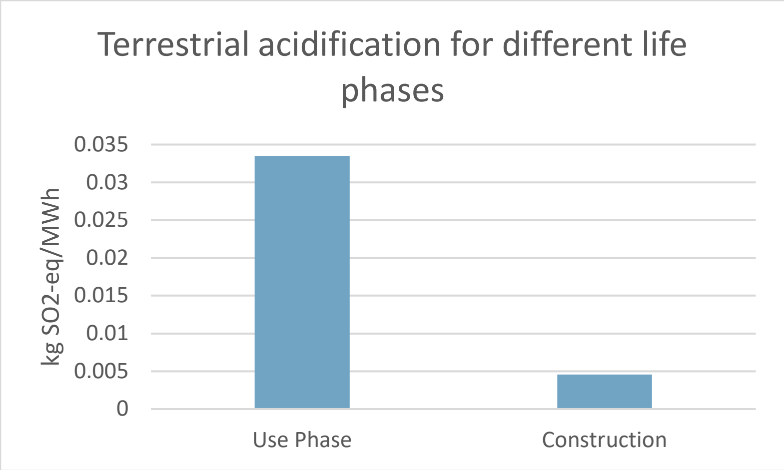

Figure 9: Contribution to terrestrial acidification for different life stages

Regarding the process contributing to the electricity use and drilling, the same observations as in the previous case are valid.

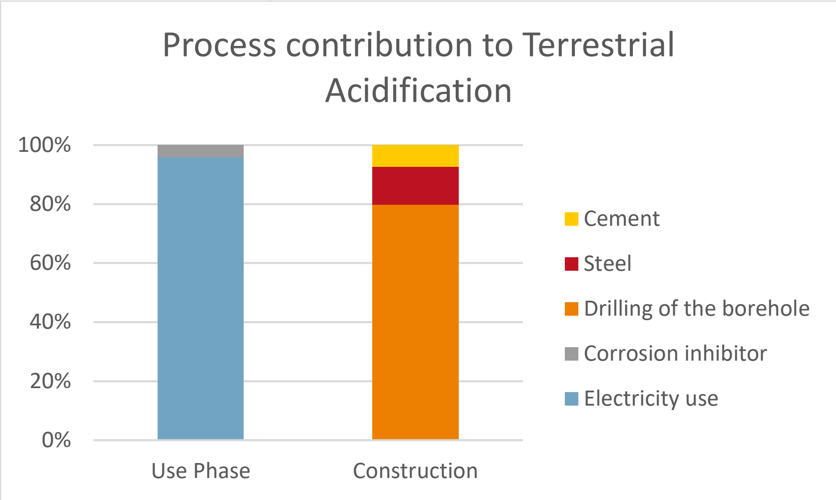

Figure 10: Percentage contribution to terrestrial acidification during construction and use phase

3.2.4 *Ozone Formation*

As in the previous cases, the use phase is the largest contributor to this impact category, generating 0,03 kg NO_x-eq/MWh in comparison with 0,008 kNO_x-eq/MWh generated by the construction phase.

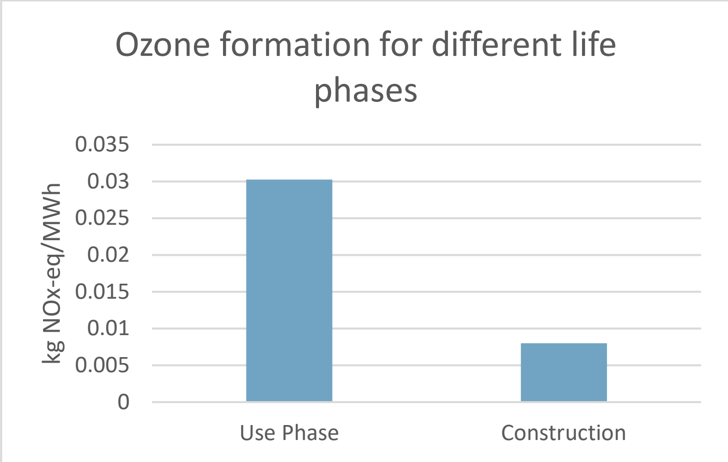

Figure 11: Contribution to ozone formation for different life stages

Regarding the process contributing to the electricity use and drilling, the same observations as in the previous case are valid.

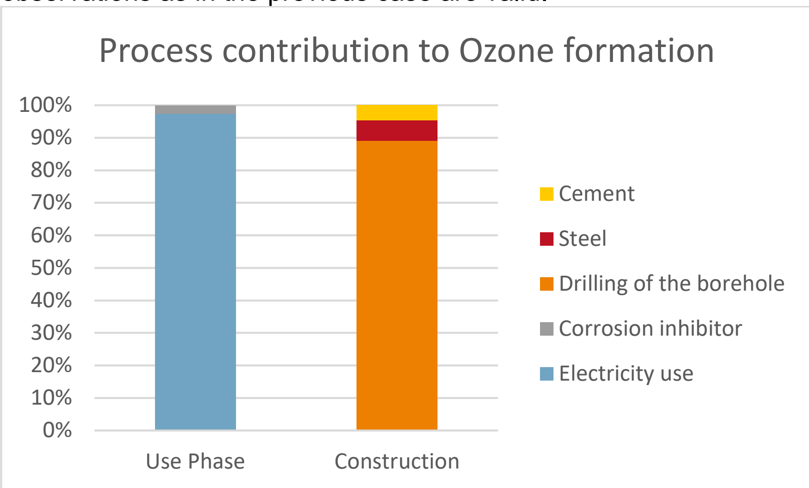

Figure 12: Percentage contribution to ozone formation during construction and use phase

3.2.5 Land use

Also in the case of land use, the main responsible for this impact category is the use phase, generating ~0,46 m^2a crop-eq/MWh in comparison with 0,01 m^2a crop-eq/MWh generated by the construction phase.

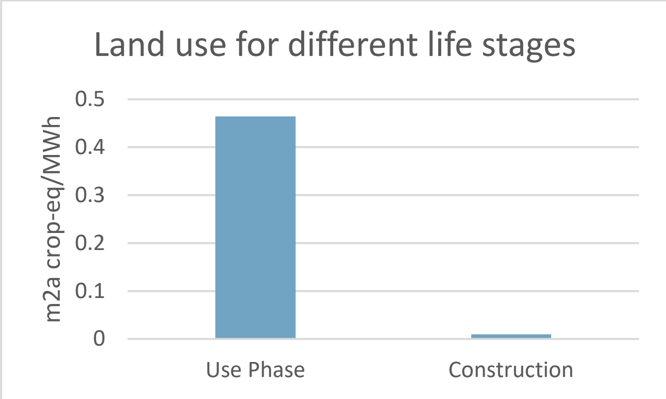

Figure 13: Land use for different life stages

Even if the process contribution looks similar to the previous cases, with the electricity consumption and drilling being the processes contributing most to this environmental impact, the background processes causing the impact are different. In the case of the electricity use, the land use is generated by the production of wood chips that are used as an input for electricity generation. In the case of the construction phase, the production of chemicals used in the drilling fluid is the main responsible process.

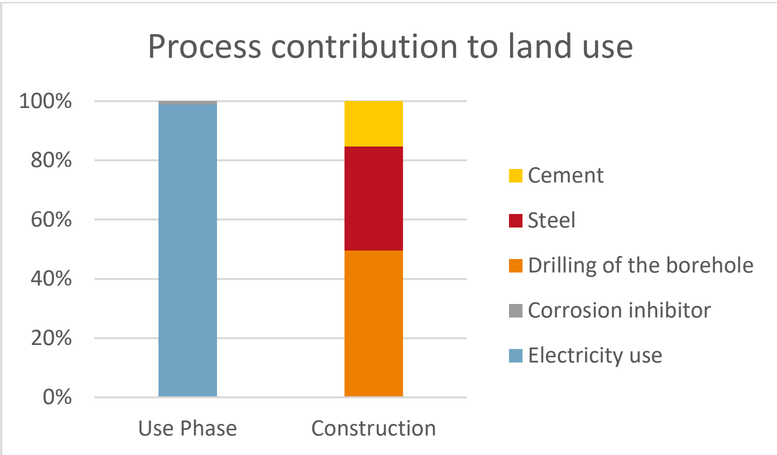

Figure 14: Percentage contribution to land use during use phase and construction phase

4 Comparison with other thermal energy sources

In order to put this work in context, it is interesting to see how the environmental profile of the thermal energy generated by geothermal sources compares with other commonly used fuels, such as natural gas or gas derived from biomass treatment.

For this exercise, the production of 1 MWh of thermal energy by means of the geothermal doublet described in the previous section was compared with the production of 1 MWh of heat produced by combusting natural gas or biogas (i.e. methane obtained by anaerobic digestion) in an industrial furnace. In the case of biogas, the caloric value of the methane obtained is the same as the natural gas and it was assumed that the efficiency of the industrial furnace would remain unchanged. The emissions generated by combusting the biogas were considered as biogenic emissions, therefore with a smaller associated impact factor. Figure 12 shows the outcomes of this comparison.

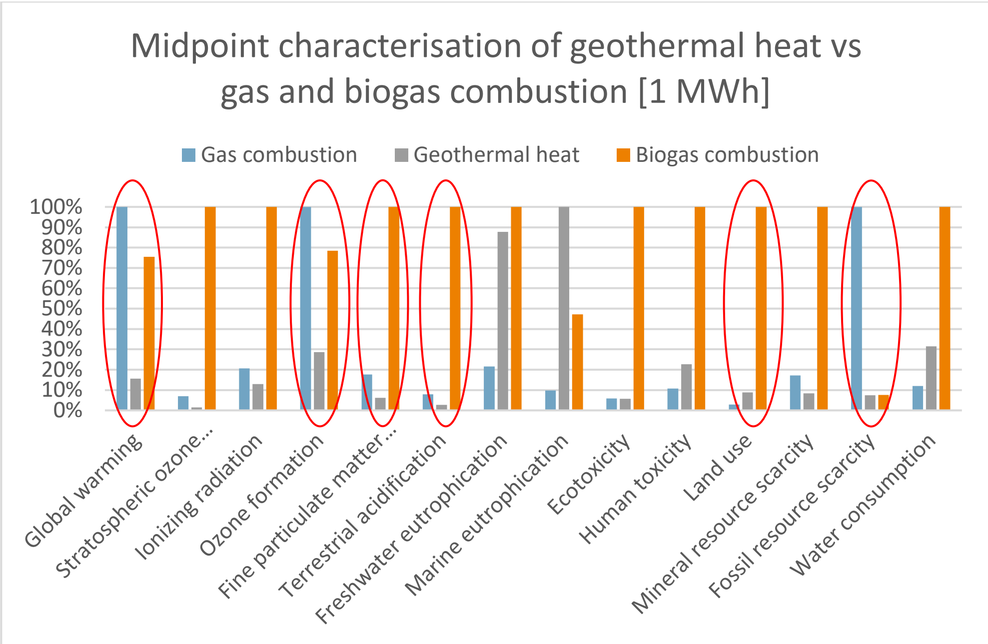

Figure 15: Comparison of the midpoint characterization of the production of 1 MWh of thermal energy by means of Natural gas combustion, geothermal heat and biogas combustion

As it can be seen from Figure 15, the different heat production methods have different impacts across the different categories considered, making it hard to draw a conclusion on which one is the “best” and which one is the “worst”. By looking at the six most relevant impact categories for the geothermal doublet (i.e. Global warming, fine particulate matter formation, Ozone formation, terrestrial acidification, Land use and Fossil resource scarcity, highlighted in the histogram above), it can be seen that the geothermal doublet always outperforms one of the alternatives and it is better than both alternatives in the case of Global warming, fine particulate matter formation, Ozone formation and terrestrial acidification.

Biogas combustion is often the worst performing process. This is due to the manure anaerobic digestion process and the biogas refining process into methane, which generate emissions of dinitrogen monoxide and hydrogen sulphide during the manure digestion process and the emissions of sulphur dioxide and hydrogen sulphide during the methane refinement process. It has to be remarked that these are process dependent and therefore this is not an exhaustive comparison with biogas.

Still, this initial comparison seems to indicate that the heat produced with geothermal energy is more environmentally friendly than the alternatives considered. Further refinement of this comparison process is necessary to draw a more solid conclusion.

5 Conclusions

The analysis carried out in this screening LCA shows that the largest environmental impacts during geothermal energy generation appear during the use phase of the geothermal installation. These are mostly due to the electricity usage.

The dominating impact category is the global warming potential, leading both to damages on human health and the ecosystems, followed by fine particulate matter formation, ozone depletion, terrestrial acidification and land use. In all these categories, electricity use generates the largest impact. The use of fossil fuels (used for electricity production and the diesel used in the drilling operations) are the main responsible factors for resource depletion.

It is important to notice that during the use phase it was assumed that 1% of the formation gasses would be emitted directly to the atmosphere. This is responsible for approximately 6% of the GWP of the use phase. For this reason, it is advisable to carry out a sensitivity analysis and further investigate this issue in future work.

Compared to other thermal energy sources, it seems that the heat generated by geothermal energy is more environmentally friendly than the combustion of natural gas or biogas obtained by anaerobic digestion of manure.

5.1 Improvements and next steps

As mentioned in the previous paragraph, the use phase is the most relevant life phase when looking at the environmental impact of a geothermal installation. For this reason, it is advisable to model this phase as accurately as possible for future work.

Furthermore, other valuable improvements should include:

- Model refinement of formation gasses, including sensitivity analysis
- Include heat pumps and/or a CHP in the surface system.
- Literature investigation on other similar LCA projects and general recommendations for the setting up of LCAs for geothermal installations (e.g. GeoEnvi project[6])
- Sensitivity analysis on the lifetime of the geothermal installation. This is important as the lifetime assumed here is 35 years (as derived from the ‘winningsplan’), However, the lifetime of a geothermal doublet is still uncertain and under debate, as geothermal systems are a relatively new energy generation system: there exist geothermal installations that have been operating already for > 40 years, but, at the same time lifetime assumptions between 25-35 years are common for studies on this topic.

Other less pressing improvements could include

- Model refinement of the drilling fluid used during the drilling process
- Model refinement of the corrosion inhibitor and derived emissions during the use phase
- Simulate the feature of electrical drilling and GRE casings (Glassfibre Reinforced Epoxy, no inhibitors needed).

[6] https://www.geoenvi.eu/

- Include heat pumps that further extract heat from the geothermal water before re-injecting it into the ground.

6 References

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7 Appendix

7.1 Endpoint Characterization

Table 5: Endpoint characterisation of the geothermal installation

Impact category	Unit	Total	Construction	Use Phase	Decommissioning
Global warming, Human health	DALY	3,41E-05	8,58E-07	3,33E-05	9,34E-10
Stratospheric ozone depletion	DALY	7,13E-09	4,92E-10	6,64E-09	9,55E-14
Ionizing radiation	DALY	1,17E-09	4,65E-11	1,12E-09	2,64E-14
Ozone formation, Human health	DALY	3,44E-08	7,11E-09	2,73E-08	2,38E-12
Fine particulate matter formation	DALY	8,58E-06	1,55E-06	7,04E-06	5,67E-10
Human carcinogenic toxicity	DALY	3,68E-07	1,07E-07	2,61E-07	1,31E-11
Human non-carcinogenic toxicity	DALY	9,70E-07	1,26E-07	8,45E-07	2,24E-11
Water consumption, Human health	DALY	1,82E-07	1,63E-08	1,65E-07	3,19E-11
Global warming, Terrestrial ecosystems	species.yr	1,03E-07	2,59E-09	1,00E-07	2,82E-12
Global warming, Freshwater ecosystems	species.yr	2,81E-12	7,07E-14	2,74E-12	7,70E-17
Ozone formation, Terrestrial ecosystems	species.yr	4,95E-09	1,03E-09	3,92E-09	3,41E-13
Terrestrial acidification	species.yr	8,10E-09	9,66E-10	7,13E-09	4,58E-13
Freshwater eutrophication	species.yr	8,93E-10	1,80E-11	8,75E-10	1,03E-14
Marine eutrophication	species.yr	1,55E-12	1,24E-14	1,53E-12	1,80E-18
Terrestrial ecotoxicity	species.yr	1,92E-10	3,24E-11	1,60E-10	2,85E-14
Freshwater ecotoxicity	species.yr	1,29E-10	2,19E-12	1,27E-10	3,56E-16
Marine ecotoxicity	species.yr	3,94E-12	6,22E-13	3,32E-12	2,14E-16
Land use	species.yr	4,21E-09	8,83E-11	4,12E-09	2,12E-13
Water consumption, Terrestrial ecosystem	species.yr	1,11E-09	1,04E-10	1,00E-09	1,96E-13
Water consumption, Aquatic ecosystems	species.yr	4,51E-14	6,90E-15	3,82E-14	9,95E-18
Mineral resource scarcity	USD2013	0,007135	0,00298	0,004153	2,12E-06
Fossil resource scarcity	USD2013	1,506356	0,097899	1,408415	4,12E-05

7.2 Midpoint characterization: Global warming

7.2.1 Construction phase

Table 6: Global warming, process contribution for construction phase

Process	Unit	Total	Deep well, for geothermal power, onshore, 6000m {GLO}|	Steel, low alloyed	Steel, unalloyed	Portland cement
Total of all processes	kg CO2 eq	**0,924541**	**0,526999**	**0,123769**	**0,039763**	**0,23401**
Remaining processes	kg CO2 eq	0,483841	0,112884	0,105281	0,035533	0,230143
Diesel, burned in diesel-electric generating set, 10MW {GLO	kg CO2 eq	0,330145	0,329732	0,000138	3,49E-05	0,00024
Diesel {RoW}| diesel production, petroleum refinery operation	kg CO2 eq	0,019741	0,019469	0,000157	3,83E-05	7,73E-05
Heat, district or industrial, other than natural gas {RoW}| heat production, at hard coal industrial furnace 1-10MW	kg CO2 eq	0,016172	0,007744	0,007495	0,000602	0,000331

Sweet gas, burned in gas turbine {RoW}	kg CO2 eq	0,007037	0,006257	0,000306	6,81E-05	0,000406
Nitric acid, without water, in 50% solution state {RoW}	kg CO2 eq	0,006421	0,006206	0,000144	2,88E-05	4,33E-05
Natural gas, vented {GLO}	kg CO2 eq	0,006184	0,005564	0,00021	5,45E-05	0,000356
Hard coal {CN}| hard coal mine operation and hard coal preparation	kg CO2 eq	0,01546	0,00487	0,007548	0,002827	0,000214
Nitric acid, without water, in 50% solution state {RER}	kg CO2 eq	0,004965	0,004712	0,000168	3,44E-05	5,12E-05
Ethylene, average {RoW}	kg CO2 eq	0,004706	0,004553	7,38E-05	1,49E-05	6,41E-05
Waste natural gas, sweet {GLO}|	kg CO2 eq	0,005082	0,004543	0,000197	4,69E-05	0,000296
Diesel {Europe without Switzerland}|	kg CO2 eq	0,004324	0,004248	3,15E-05	9,34E-06	3,48E-05
Transport, freight, sea, tanker for petroleum {GLO}|	kg CO2 eq	0,003854	0,003492	0,000114	3,22E-05	0,000216
Waste natural gas, sour {GLO}	kg CO2 eq	0,003692	0,003333	0,000113	3,13E-05	0,000215
Ammonia, liquid {RoW}	kg CO2 eq	0,00336	0,003284	5,13E-05	9,76E-06	1,45E-05
Hazardous waste, for incineration {RoW}	kg CO2 eq	0,003223	0,003219	2,02E-06	5,49E-07	1,38E-06
Diesel, burned in building machine {GLO}	kg CO2 eq	0,006334	0,002889	0,001741	0,000397	0,001307

7.2.2 *Use Phase*

Table 7: Global warming, process contribution for use phase

Process	**Unit**	**Total**	**Geothermal doublet_use**	**Corrosion inhibitor**	**Methane formation gas burned in industrial furnace**	**Electricity**
Total of all processes	kg CO2 eq	**35,81053**	**2,273353**	**0,421297**	**9,958326**	**23,157554**
Remaining processes	kg CO2 eq	15,09615	2,273353	0,387042	9,958296	2,4774605
Electricity, high voltage {NL}| electricity production, hard coal | Cut-off, U	kg CO2 eq	8,679691	0	0,000896	7,3E-07	8,6787937
Electricity, high voltage {DE}| electricity production, lignite | Cut-off, U	kg CO2 eq	1,698366	0	0,004972	4,2E-06	1,69339
Electricity, high voltage {NL}| electricity production, natural gas, combined cycle power plant | Cut-off, U	kg CO2 eq	1,661277	0	0,000171	1,39E-07	1,661105
Electricity, high voltage {NL}| electricity production, natural gas, conventional power plant | Cut-off, U	kg CO2 eq	1,452987	0	0,00015	1,21E-07	1,4528368
Electricity, high voltage {NL}| treatment of blast furnace	kg CO2 eq	1,405047	0	0,000145	1,17E-07	1,4049022

gas, in power plant | Cut-off, U						
Electricity, high voltage {NL}| heat and power co-generation, hard coal | Cut-off, U	kg CO2 eq	1,18532	0	0,000122	9,9E-08	1,185198
Electricity, high voltage {NL}| heat and power co-generation, natural gas, conventional power plant, 100MW electrical | Cut-off, U	kg CO2 eq	0,993004	0	0,000102	8,3E-08	0,99290143
Electricity, high voltage {NL}| heat and power co-generation, natural gas, combined cycle power plant, 400MW electrical | Cut-off, U	kg CO2 eq	0,911124	0	9,45E-05	7,93E-08	0,91102944
Electricity, high voltage {DE}| electricity production, hard coal | Cut-off, U	kg CO2 eq	0,887409	0	0,002598	2,19E-06	0,88480861
Hard coal {Europe, without Russia and Turkey}| hard coal mine operation and hard coal preparation | Cut-off, U	kg CO2 eq	0,624197	0	0,000751	1,05E-06	0,62344419
Hard coal {RU}| hard coal mine operation and hard coal preparation | Cut-off, U	kg CO2 eq	0,288958	0	0,000399	2,66E-06	0,28855556
Electricity, high voltage {NL}| heat and power co-generation, oil | Cut-off, U	kg CO2 eq	0,215729	0	2,23E-05	1,8E-08	0,21570685
Transport, freight, sea, bulk carrier for dry goods {GLO}| transport, freight, sea, bulk carrier for dry goods | Cut-off, U	kg CO2 eq	0,194062	0	0,000444	1,34E-05	0,19360446
Electricity, high voltage {DE}| heat and power co-generation, natural gas, conventional power plant, 100MW	kg CO2 eq	0,169898	0	0,000497	4,17E-07	0,16940039

electrical | Cut-off, U						
Transport, pipeline, long distance, natural gas {RU}| processing | Cut-off, U	kg CO2 eq	0,180189	0	0,011875	2,63E-06	0,16831149
Electricity, medium voltage {RU}| natural gas, burned in gas turbine, for compressor station | Cut-off, U	kg CO2 eq	0,167121	0	0,011014	2,44E-06	0,15610497

7.3 Midpoint characterisation: Fine particulate matter formation

7.3.1 Construction Phase

Table 8: Fine particulate matter formation, process contribution for the construction phase

Process	**Unit**	**Total**	**Deep well, for geothermal power, onshore, 6000m**	**Steel, low-alloyed**	**Steel, unalloyed**	**Cement, Portland**
Total of all processes	kg PM2.5 eq	**0,002459**	**0,001939**	**3,18E-04**	**7,58E-05**	**1,26E-04**
Remaining processes	kg PM2.5 eq	0,000734	0,000252	2,93E-04	7,21E-05	1,17E-04
Diesel, burned in diesel-electric generating set, 10MW {GLO}| diesel, burned in diesel-electric generating set, 10MW | Cut-off, U	kg PM2.5 eq	0,001497	0,001496	6,28E-07	1,58E-07	1,09E-06
Waste natural gas, sour {GLO}| treatment of, burned in production flare | Cut-off, U	kg PM2.5 eq	7,84E-05	7,08E-05	2,39E-06	6,64E-07	4,56E-06
Diesel {RoW}| diesel production, petroleum refinery operation | Cut-off, U	kg PM2.5 eq	3,90E-05	3,85E-05	3,10E-07	7,58E-08	1,53E-07
Transport, freight, sea, tanker for petroleum {GLO}| transport, freight, sea, tanker for petroleum | Cut-off, U	kg PM2.5 eq	2,61E-05	2,36E-05	7,70E-07	2,18E-07	1,46E-06
Transport, freight, sea, container ship {GLO}| transport, freight, sea, container ship | Cut-off, U	kg PM2.5 eq	1,94E-05	1,86E-05	5,89E-07	7,32E-08	1,11E-07
Heat, district or industrial, other than natural gas {RoW}| heat production, at hard coal industrial furnace 1-10MW | Cut-off, U	kg PM2.5 eq	3,28E-05	1,57E-05	1,52E-05	1,22E-06	6,71E-07
Electricity, high voltage {ID}|	kg PM2.5 eq	1,95E-05	1,27E-05	5,16E-06	1,22E-06	3,90E-07

electricity production, lignite | Cut-off, U						
Sulfuric acid {RoW}| production | Cut-off, U	kg PM2.5 eq	1,19E-05	1,17E-05	1,63E-07	7,26E-08	1,27E-08

7.3.2 *Use Phase*

Table 9: Fine particulate matter formation, process contribution for use phase

Process	**Unit**	**Total**	**Corrosion inhibitor**	**Methane formation gas burned in industrial furnace**	**Electricity**
Total of all processes	kg PM2.5 eq	**0,011127**	**0,000472**	**2,13E-06**	**0,010653**
Remaining processes	kg PM2.5 eq	0,003162	0,000381	1,92E-06	0,002779
Electricity, high voltage {NL}| electricity production, hard coal | Cut-off, U	kg PM2.5 eq	0,002592	2,68E-07	2,18E-10	0,002592
Transport, freight, sea, bulk carrier for dry goods {GLO}| transport, freight, sea, bulk carrier for dry goods | Cut-off, U	kg PM2.5 eq	0,001301	2,98E-06	8,98E-08	0,001298
Waste gypsum {Europe without Switzerland}| treatment of waste gypsum, sanitary landfill | Cut-off, U	kg PM2.5 eq	0,000887	1,35E-06	1,89E-09	0,000886
Electricity, high voltage {DE}| electricity production, lignite | Cut-off, U	kg PM2.5 eq	0,000437	1,28E-06	1,08E-09	0,000436
Electricity, high voltage {NL}| heat and power co-generation, hard coal | Cut-off, U	kg PM2.5 eq	0,000354	3,65E-08	2,96E-11	0,000354
Sour gas, burned in gas turbine {RoW}| processing | Cut-off, U	kg PM2.5 eq	0,000341	3,99E-05	9,87E-09	0,000301
Electricity, high voltage {DE}| electricity production, hard coal | Cut-off, U	kg PM2.5 eq	0,000291	8,51E-07	7,18E-10	0,00029
Blasting {RoW}| processing | Cut-off, U	kg PM2.5 eq	0,000291	2,82E-06	1,86E-08	0,000288
Electricity, high voltage {RU}| heat and power co-generation, lignite | Cut-off, U	kg PM2.5 eq	0,000176	2,53E-06	1,88E-08	0,000174
Transport, freight train {RoW}| diesel | Cut-off, U	kg PM2.5 eq	0,000164	2,37E-06	1,11E-08	0,000162
Electricity, high voltage {NL}| electricity production, natural gas, conventional power plant | Cut-off, U	kg PM2.5 eq	0,000158	1,63E-08	1,32E-11	0,000158
Copper {RAS}| production, primary | Cut-off, U	kg PM2.5 eq	0,000168	1,46E-05	8,38E-09	0,000153
Waste natural gas, sour {GLO}| treatment of, burned in production flare | Cut-off, U	kg PM2.5 eq	0,000169	1,66E-05	1,56E-08	0,000152
Blasting {RER}| processing | Cut-off, U	kg PM2.5 eq	0,000147	1,45E-06	9,31E-09	0,000146
Biogas {RoW}| anaerobic digestion of manure | Cut-off, U	kg PM2.5 eq	0,000144	6,19E-07	6,84E-10	0,000143
Diesel, burned in building machine {GLO}| processing | Cut-off, U	kg PM2.5 eq	0,000133	3,67E-06	2,66E-08	0,00013

Electricity, high voltage {NL}| heat and power co-generation, wood chips, 6667 kW, state-of-the-art 2014 | Cut-off, U	kg PM2.5 eq	0,000108	1,11E-08	8,99E-12	0,000108
Electricity, high voltage {NL}| electricity production, natural gas, combined cycle power plant | Cut-off, U	kg PM2.5 eq	0,000107	1,10E-08	8,94E-12	0,000107

7.4 Midpoint characterisation: Terrestrial acidification

7.4.1 Construction Phase

Table 10: Terrestrial acidification, process contribution for construction phase

Process	**Unit**	**Total**	**Deep well, for geothermal power, onshore, 6000m**	**Steel, low-alloyed**	**Steel, unalloyed**	**Cement, Portland**
Total of all processes	kg SO2 eq	**0,004556**	**0,003642**	**4,42E-04**	**0,000119**	**0,000353**
Remaining processes	kg SO2 eq	0,001336	0,00053	3,74E-04	0,00011	0,000322
Diesel, burned in diesel-electric generating set, 10MW {GLO}| diesel, burned in diesel-electric generating set, 10MW | Cut-off, U	kg SO2 eq	0,002458	0,002455	1,03E-06	2,60E-07	1,78E-06
Waste natural gas, sour {GLO}| treatment of, burned in production flare | Cut-off, U	kg SO2 eq	0,000269	0,000243	8,22E-06	2,28E-06	1,57E-05
Diesel {RoW}| diesel production, petroleum refinery operation | Cut-off, U	kg SO2 eq	0,000119	0,000117	9,41E-07	2,30E-07	4,64E-07
Transport, freight, sea, tanker for petroleum {GLO}| transport, freight, sea, tanker for petroleum | Cut-off, U	kg SO2 eq	8,21E-05	7,43E-05	2,42E-06	6,86E-07	4,6E-06
Transport, freight, sea, container ship {GLO}| transport, freight, sea, container ship | Cut-off, U	kg SO2 eq	6,11E-05	5,86E-05	1,85E-06	2,30E-07	3,5E-07
Heat, district or industrial, other than natural gas {RoW}| heat production, at hard coal industrial furnace 1-10MW | Cut-off, U	kg SO2 eq	0,0001	4,81E-05	4,65E-05	3,74E-06	2,05E-06
Sulfuric acid {RoW}| production | Cut-off, U	kg SO2 eq	4,10E-05	4,02E-05	5,61E-07	2,50E-07	4,39E-08
Copper {RAS}| production, primary | Cut-off, U	kg SO2 eq	4,22E-05	2,95E-05	6,29E-06	7,31E-07	5,7E-06
Diesel {Europe without Switzerland}| diesel production, petroleum refinery operation | Cut-off, U	kg SO2 eq	2,60E-05	2,55E-05	1,89E-07	5,61E-08	2,09E-07
Sulfuric acid {RER}| production | Cut-off, U	kg SO2 eq	2,13E-05	2,11E-05	1,13E-07	2,58E-08	6,21E-08

7.4.2 *Use Phase*

Table 11: Terrestrial Acidification, process contribution for use phase

Process	Unit	Total	Corrosion inhibitor	Methane formation gas burned in industrial furnace	Electricity
Total of all processes	kg SO2 eq	**0,033513795**	**0,00141343**	**3,40E-06**	**0,032097**
Remaining processes	kg SO2 eq	0,008325147	0,00111828	2,84E-06	0,007204
Electricity, high voltage {NL}| electricity production, hard coal | Cut-off, U	kg SO2 eq	0,008218545	8,48E-07	6,91E-10	0,008218
Transport, freight, sea, bulk carrier for dry goods {GLO}| transport, freight, sea, bulk carrier for dry goods | Cut-off, U	kg SO2 eq	0,00409765	9,38E-06	2,83E-07	0,004088
Waste gypsum {Europe without Switzerland}| treatment of waste gypsum, sanitary landfill | Cut-off, U	kg SO2 eq	0,003058169	4,67E-06	6,53E-09	0,003053
Electricity, high voltage {DE}| electricity production, lignite | Cut-off, U	kg SO2 eq	0,001224359	3,58E-06	3,03E-09	0,001221
Blasting {RoW}| processing | Cut-off, U	kg SO2 eq	0,001218777	1,18E-05	7,82E-08	0,001207
Biogas {RoW}| anaerobic digestion of manure | Cut-off, U	kg SO2 eq	0,00117239	5,05E-06	5,59E-09	0,001167
Electricity, high voltage {NL}| heat and power co-generation, hard coal | Cut-off, U	kg SO2 eq	0,001122345	1,16E-07	9,38E-11	0,001122
Sour gas, burned in gas turbine {RoW}| processing | Cut-off, U	kg SO2 eq	0,001173772	0,00013739	3,40E-08	0,001036
Electricity, high voltage {DE}| electricity production, hard coal | Cut-off, U	kg SO2 eq	0,000835514	2,45E-06	2,07E-09	0,000833
Blasting {RER}| processing | Cut-off, U	kg SO2 eq	0,000616718	6,08E-06	3,90E-08	0,000611
Copper {RAS}| production, primary | Cut-off, U	kg SO2 eq	0,00057811	5,03E-05	2,89E-08	0,000528
Waste natural gas, sour {GLO}| treatment of, burned in production flare | Cut-off, U	kg SO2 eq	0,000578241	5,69E-05	5,36E-08	0,000521
Electricity, high voltage {NL}| electricity production, natural gas, conventional power plant | Cut-off, U	kg SO2 eq	0,000474648	4,90E-08	3,97E-11	0,000475
Transport, freight train {RoW}| diesel | Cut-off, U	kg SO2 eq	0,000445894	6,44E-06	3,01E-08	0,000439
Electricity, high voltage {NL}| heat and power co-generation, wood chips, 6667 kW, state-of-the-art 2014 | Cut-off, U	kg SO2 eq	0,000373516	3,85E-08	3,12E-11	0,000373

7.5 Midpoint characterisation: Ozone formation

7.5.1 Construction Phase

Table 12: Ozone formation, process contribution for the construction phase

Process	**Unit**	**Total**	**Deep well, for geothermal power, onshore, 6000m**	**Steel, low-alloyed**	**Steel, unalloyed**	**Cement, Portland**
Total of all processes	kg NOx eq	**0,008**	**0,007128**	**3,72E-04**	**0,000109**	**0,000391**
Remaining processes	kg NOx eq	0,001329	0,000525	3,40E-04	0,000101	0,000363
Diesel, burned in diesel-electric generating set, 10MW {GLO}| diesel, burned in diesel-electric generating set, 10MW | Cut-off, U	kg NOx eq	0,00621	0,006202	2,60E-06	6,56E-07	4,5E-06
Lubricating oil {RoW}| production | Cut-off, U	kg NOx eq	0,000188	0,000187	1,00E-06	4,17E-08	1,22E-07
Transport, freight, sea, tanker for petroleum {GLO}| transport, freight, sea, tanker for petroleum | Cut-off, U	kg NOx eq	7,98E-05	7,23E-05	2,36E-06	6,67E-07	4,47E-06
Transport, freight, sea, container ship {GLO}| transport, freight, sea, container ship | Cut-off, U	kg NOx eq	6,30E-05	6,05E-05	1,91E-06	2,38E-07	3,61E-07
Diesel, burned in building machine {GLO}| processing | Cut-off, U	kg NOx eq	9,12E-05	4,16E-05	2,51E-05	5,71E-06	1,88E-05
Lubricating oil {RER}| production | Cut-off, U	kg NOx eq	3,99E-05	3,97E-05	5,12E-08	1,31E-08	1,41E-07

7.5.2 Use Phase

Table 13: Ozone formation, process contribution for use phase

Process	Unit	Total	Corrosion inhibitor	Methane formation gas burned in industrial furnace	Electricity
Total of all processes	kg NOx eq	0,030279065	0,00076857	2,61E-06	0,029508
Remaining processes	kg NOx eq	0,004340215	0,00061134	1,89E-06	0,003727
Electricity, high voltage {NL}| electricity production, hard coal | Cut-off, U	kg NOx eq	0,007268648	7,50E-07	6,11E-10	0,007268
Transport, freight, sea, bulk carrier for dry goods {GLO}| transport, freight, sea, bulk carrier for dry goods | Cut-off, U	kg NOx eq	0,003801513	8,71E-06	2,62E-07	0,003793
Blasting {RoW}| processing | Cut-off, U	kg NOx eq	0,00180844	1,75E-05	1,16E-07	0,001791
Electricity, high voltage {NL}| electricity production, natural gas, conventional power plant | Cut-off, U	kg NOx eq	0,001302363	1,34E-07	1,09E-10	0,001302

Transport, freight train {RoW}| diesel | Cut-off, U	kg NOx eq	0,001232246	1,78E-05	8,32E-08	0,001214
Electricity, high voltage {DE}| electricity production, lignite | Cut-off, U	kg NOx eq	0,001117749	3,27E-06	2,76E-09	0,001114
Electricity, high voltage {NL}| heat and power co-generation, hard coal | Cut-off, U	kg NOx eq	0,000992625	1,02E-07	8,29E-11	0,000993
Blasting {RER}| processing | Cut-off, U	kg NOx eq	0,000915097	9,03E-06	5,79E-08	0,000906
Electricity, high voltage {NL}| electricity production, natural gas, combined cycle power plant | Cut-off, U	kg NOx eq	0,000812023	8,38E-08	6,79E-11	0,000812
Transport, freight, inland waterways, barge {RER}| processing | Cut-off, U	kg NOx eq	0,000719373	4,46E-06	1,26E-08	0,000715
Electricity, high voltage {NL}| heat and power co-generation, natural gas, conventional power plant, 100MW electrical | Cut-off, U	kg NOx eq	0,000692381	7,14E-08	5,79E-11	0,000692
Diesel, burned in building machine {GLO}| processing | Cut-off, U	kg NOx eq	0,0006616	1,82E-05	1,32E-07	0,000643
Transport, freight train {Europe without Switzerland}| diesel | Cut-off, U	kg NOx eq	0,000625187	4,90E-06	5,42E-09	0,00062
Electricity, high voltage {DE}| electricity production, hard coal | Cut-off, U	kg NOx eq	0,000590946	1,73E-06	1,46E-09	0,000589
Electricity, medium voltage {RU}| natural gas, burned in gas turbine, for compressor station | Cut-off, U	kg NOx eq	0,000586365	3,86E-05	8,55E-09	0,000548
Electricity, high voltage {NL}| heat and power co-generation, oil | Cut-off, U	kg NOx eq	0,000532273	5,49E-08	4,45E-11	0,000532
Electricity, high voltage {NL}| treatment of blast furnace gas, in power plant | Cut-off, U	kg NOx eq	0,000496286	5,12E-08	4,15E-11	0,000496
Electricity, high voltage {NL}| heat and power co-generation, wood chips, 6667 kW, state-of-the-art 2014 | Cut-off, U	kg NOx eq	0,000468573	4,83E-08	3,92E-11	0,000469
Electricity, high voltage {NL}| heat and power co-generation, natural gas, combined cycle power plant, 400MW electrical | Cut-off, U	kg NOx eq	0,000445352	4,62E-08	3,88E-11	0,000445
Transport, freight train {US}| diesel | Cut-off, U	kg NOx eq	0,000426057	1,12E-06	1,52E-08	0,000425
Diesel, burned in diesel-electric generating set, 10MW {GLO}| diesel, burned in diesel-electric generating set, 10MW | Cut-off, U	kg NOx eq	0,000443753	3,05E-05	1,88E-08	0,000413

7.6 Midpoint characterisation: Land use

7.6.1 Construction Phase

Table 14: Land use, process contribution for construction phase

Process	Unit	Total	Deep well, for geothermal power, onshore, 6000m	Steel, low-alloyed	Steel, unalloyed	Cement, Portland
Total of all processes	m2a crop eq	**0,009953**	**0,004949**	**0,002766**	**0,000609**	**0,001628**
Remaining processes	m2a crop eq	0,003774	0,001602	0,00117	0,000239	0,000763
Road {RoW}| road construction | Cut-off, U	m2a crop eq	0,001147	0,000476	0,000293	8,93E-05	0,000289
Sawlog and veneer log, softwood, measured as solid wood under bark {RoW}| softwood forestry, pine, sustainable forest management | Cut-off, U	m2a crop eq	0,000532	0,000358	9,9E-05	1,17E-05	6,33E-05
Sawlog and veneer log, softwood, measured as solid wood under bark {RoW}| softwood forestry, spruce, sustainable forest management | Cut-off, U	m2a crop eq	0,000514	0,000346	9,57E-05	1,13E-05	6,11E-05
Phosphoric acid, fertiliser grade, without water, in 70% solution state {RoW}| phosphoric acid production, dihydrate process | Cut-off, U	m2a crop eq	0,000279	0,000278	1,18E-06	2,63E-07	1,84E-07
Onshore petroleum field infrastructure {GLO}| construction | Cut-off, U	m2a crop eq	0,0003	0,000271	9,1E-06	2,54E-06	1,74E-05
Residual material landfill {RoW}| construction | Cut-off, U	m2a crop eq	0,000302	0,000219	7,34E-05	7,88E-06	1,46E-06
Sawlog and veneer log, softwood, measured as solid wood under bark {CA-QC}| softwood forestry, mixed species, boreal forest | Cut-off, U	m2a crop eq	0,000279	0,00018	6,36E-05	7,67E-06	2,79E-05
Railway track {RoW}| construction | Cut-off, U	m2a crop eq	0,000314	0,000164	9,23E-05	3,28E-05	2,54E-05
Phosphoric acid, fertiliser grade, without water, in 70% solution state {US}| phosphoric acid production, dihydrate process | Cut-off, U	m2a crop eq	0,00015	0,000149	6,33E-07	1,41E-07	9,85E-08
Sawlog and veneer log,	m2a crop eq	0,000533	0,000143	0,000232	8,42E-05	7,3E-05

hardwood, measured as solid wood under bark {DE}| hardwood forestry, beech, sustainable forest management | Cut-off, U						
Hard coal {CN}| hard coal mine operation and hard coal preparation | Cut-off, U	m2a crop eq	0,000448	0,000141	0,000219	8,19E-05	6,21E-06
Process-specific burdens, residual material landfill {RoW}| processing | Cut-off, U	m2a crop eq	0,00018	0,000131	4,42E-05	4,25E-06	9,69E-07
Wood chips, wet, measured as dry mass {RoW}| hardwood forestry, birch, sustainable forest management | Cut-off, U	m2a crop eq	0,000266	0,000128	0,000122	1,10E-05	5,16E-06
Wood chips, wet, measured as dry mass {SE}| hardwood forestry, birch, sustainable forest management | Cut-off, U	m2a crop eq	0,000306	9,90E-05	3,93E-05	5,16E-06	0,000163
Wood chips, wet, measured as dry mass {RoW}| softwood forestry, pine, sustainable forest management | Cut-off, U	m2a crop eq	0,000201	9,65E-05	9,21E-05	8,30E-06	3,9E-06
Wood chips, wet, measured as dry mass {RoW}| softwood forestry, spruce, sustainable forest management | Cut-off, U	m2a crop eq	0,000195	9,36E-05	8,94E-05	8,05E-06	3,78E-06
Wood chips, wet, measured as dry mass {SE}| softwood forestry, pine, sustainable forest management | Cut-off, U	m2a crop eq	0,000233	7,54E-05	2,99E-05	3,93E-06	0,000124

7.6.2 Use Phase

Table 15: Land use, process contribution for use phase

Process	**Unit**	**Total**	**Corrosion inhibitor**	**Methane formation gas burned in industrial furnace**	**Electricity**
Total of all processes	m2a crop eq	**0,46401475**	**0,004603**	**1,92E-05**	**0,459393**
Remaining processes	m2a crop eq	0,057530066	0,002972	1,45E-05	0,054544
Wood chips, wet, measured as dry mass {SE}| hardwood forestry, birch, sustainable forest management | Cut-off, U	m2a crop eq	0,094659913	0,000385	3,80E-07	0,094275
Wood chips, wet, measured as dry mass	m2a crop eq	0,072106435	0,000293	2,90E-07	0,071813

{SE}| softwood forestry, pine, sustainable forest management | Cut-off, U					
Wood chips, wet, measured as dry mass {SE}| softwood forestry, spruce, sustainable forest management | Cut-off, U	m2a crop eq	0,07000526	0,000284	2,81E-07	0,069721
Wood chips, wet, measured as dry mass {DE}| hardwood forestry, beech, sustainable forest management | Cut-off, U	m2a crop eq	0,047861494	0,000194	1,92E-07	0,047667
Sawlog and veneer log, hardwood, measured as solid wood under bark {DE}| hardwood forestry, beech, sustainable forest management | Cut-off, U	m2a crop eq	0,024474092	9,62E-05	1,86E-06	0,024376
Wood chips, wet, measured as dry mass {DE}| softwood forestry, spruce, sustainable forest management | Cut-off, U	m2a crop eq	0,019827731	8,06E-05	7,96E-08	0,019747
Wood chips, wet, measured as dry mass {DE}| softwood forestry, pine, sustainable forest management | Cut-off, U	m2a crop eq	0,016431347	6,68E-05	6,60E-08	0,016365
Hard coal {Europe, without Russia and Turkey}| hard coal mine operation and hard coal preparation | Cut-off, U	m2a crop eq	0,010770852	1,30E-05	1,81E-08	0,010758
Hard coal {RNA}| hard coal mine operation and hard coal preparation | Cut-off, U	m2a crop eq	0,010064756	2,43E-05	3,49E-07	0,01004
Railway track {RoW}| construction | Cut-off, U	m2a crop eq	0,010146329	0,000113	5,81E-07	0,010033
Wood chips, wet, measured as dry mass {DE}| hardwood forestry, oak, sustainable forest management | Cut-off, U	m2a crop eq	0,009118633	3,71E-05	3,66E-08	0,009082
Hard coal {RU}| hard coal mine operation and hard coal preparation | Cut-off, U	m2a crop eq	0,008786381	1,21E-05	8,09E-08	0,008774
Hard coal {RLA}| hard coal mine operation and hard coal preparation | Cut-off, U	m2a crop eq	0,006396361	8,39E-06	3,75E-08	0,006388
Sawlog and veneer log, hardwood, measured as solid wood under bark {DE}| hardwood forestry, oak, sustainable forest management | Cut-off, U	m2a crop eq	0,005835101	2,29E-05	4,43E-07	0,005812

7.7 Comparison with other thermal energy sources

Table 16: Midpoint characterisation of different thermal energy production methods

Impact category	**Unit**	**Natural gas combustion in industrial furnace**	**Geothermal doublet**	**Biogas combustion in industrial furnace**
Global warming	kg CO2 eq	2,36E+02	3,67E+01	178,3233
Stratospheric ozone depletion	kg CFC11 eq	6,65E-05	1,34E-05	0,000965
Ionizing radiation	kBq Co-60 eq	0,219325	0,137517	1,065075

Ozone formation, Human health	kg NOx eq	0,129558	0,037672	0,102673
Fine particulate matter formation	kg PM2.5 eq	0,03855	0,013588	0,21808
Ozone formation, Terrestrial ecosystems	kg NOx eq	0,135462	0,038284	0,105128
Terrestrial acidification	kg SO2 eq	0,113315	0,038073	1,431345
Freshwater eutrophication	kg P eq	3,27E-04	0,001333	0,001518
Marine eutrophication	kg N eq	8,86E-05	0,000907	0,000428
Terrestrial ecotoxicity	kg 1,4-DCB	16,70161	16,62874	294,1192
Freshwater ecotoxicity	kg 1,4-DCB	0,007289	0,185491	0,032934
Marine ecotoxicity	kg 1,4-DCB	0,441188	0,037271	0,204383
Human carcinogenic toxicity	kg 1,4-DCB	0,200818	0,10499	0,564562
Human non-carcinogenic toxicity	kg 1,4-DCB	1,874262	4,246707	18,69096
Land use	m2a crop eq	0,155183	0,474009	5,364085
Mineral resource scarcity	kg Cu eq	0,060667	0,029823	0,354679
Fossil resource scarcity	kg oil eq	91,70769	6,817162	6,98204
Water consumption	m3	0,07585	0,198707	0,632632