Frick, S., Kaltschmitt, M., Schröder, G. (2010): Life cycle assessment of geothermal binary power plants using enhanced low-temperature reservoirs. - Energy, 35, 5, 2281-2294

DOI: 10.1016/j.energy.2010.02.016

Life cycle assessment of geothermal binary power plants using enhanced low temperature reservoirs

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Received:

Abstract

Geothermal binary power plants that use low-temperature heat sources have gained increasing interest in the recent years due to political efforts to reduce greenhouse gas emissions and the consumption of finite energy resources. The construction of such plants requires large amounts of energy and material. Hence, the question arises if geothermal binary power plants are also environmentally promising from a cradle-to-grave point of view. In this context, a comprehensive Life Cycle Analysis (LCA) on geothermal power production from EGS (enhanced geothermal systems) low-temperature reservoirs is performed. The results of the analysis show that the environmental impacts are very much influenced by the geological conditions that can be obtained at a specific site. At sites with (above-) average geological conditions, geothermal binary power generation can significantly contribute to more sustainable power supply. At sites with less favorable conditions, only certain plant designs can make up for the energy and material input to lock up the geothermal reservoir by the provided energy. The main aspects of environmentally sound plants are enhancement of the reservoir productivity, reliable design of the deep wells and an efficient utilization of the geothermal fluid for net power and district heat production.

1 Introduction

The use of geothermal energy for electricity and/or heat production has gained increasing interest due to the political goals of reducing greenhouse gas emissions, reducing the

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consumption of finite energy resources, and increasing security of energy supply. Geothermal energy provides power and/or heat from a renewable source of energy that is independent of season and time of day and offers a significant potential on a world wide scale (e.g. [1]). Only a small part of this huge potential is currently being used. The globally installed electrical power in 2007 summed up to about 9 GW [2]. The largest share of this capacity is generated from high-enthalpy or high-temperature geothermal reservoirs that are located at exceptionally favorable geological sites (e.g. Italy, Iceland, Philippines). Less than 1 % of the capacity, but the predominant part of the still unexploited geothermal potential, is located outside exceptionally favorable geological areas and is found in reservoirs of low temperature (typically between 100 and 200 °C), large depths and/or low natural permeabilities.

The technical requirements to effectively exploit reservoirs with less promising characteristics are quite significant. To tap geological layers with temperatures above 100 °C, deep wells are needed. Drilling and completion of such wells, as well technical measures to enhance geothermal reservoirs in order to obtain higher permeabilities (enhanced geothermal systems, EGS) require large amounts of energy and material. On the surface, the geothermal heat is transferred to a binary conversion cycle (and at some sites additionally to a district heating system). In the binary unit, a working fluid with low boiling point is circulated because the direct use of the geothermal fluid in a power conversion cycle is not efficient from a thermodynamic point of view. Electricity generation using low temperatures heat sources is generally characterized by relatively low conversion efficiencies.

Due to the technical challenges associated with the assessment and energetic use of low-temperature geothermal heat sources, the question arises if the environmental benefit of geothermal energy supply also exists for such reservoirs. Putting this question is furthermore important because most of the low temperature geothermal binary power plants presently need to be subsidized from the public purse due to the still challenging economic performance.

In this context, the goal of this paper is it to analyze selected environmental effects of power production from low-temperature geothermal resources based on the Life Cycle Assessment (LCA) methodology. As with the evaluation of any technology still at the beginning of its learning curve and thus on the borderline to market implementation, the assessment of geothermal binary power plants lacks sufficient and assured data. Moreover, geothermal power production from low-temperature resources is dominated by site specific preconditions and plant specifications varying considerably between different locations.

Based on existing publications ([3], [4], [5], [6], [7]), this paper will therefore present a more comprehensive evaluation of geothermal binary plants that provide power as well as power and heat. First, selected geothermal binary power plants representative for the current state of technology in Europe are defined as base cases and the environmental key figures of these base cases are analyzed. Focus is given to the impact of the different life cycle stages, the effect of data uncertainties and the impact of changing site and plant parameters. Afterwards, the range of the environmental performance associated with low temperature geothermal binary power plants is estimated by means of “worst case” and “best case” scenarios. In order to classify the environmental performance of the analyzed plants within the energy sector, the results of the base case evaluation and the scenario analysis are discussed in relation to a reference electricity mix and a reference heat mix. Based on all the results, conclusions and recommendations are drawn.

2 Methodical approach

The idea behind an LCA is that environmental impacts of a product (such as the power generated in geothermal binary power plants) are not limited to the power production process itself. Substantial environmental impacts can also occur within the pre-chains of installed components (e.g. diesel fuel supply and consumption for drilling the deep wells), used materials (e.g. steel production and supply for the completion of the wells) and necessary services (e.g. disposal of disused components and waste material). Within an LCA, a product is hence investigated throughout the overall life cycle (i.e. from "cradle to grave"). Regarding geothermal binary power plants, this approach includes environmental impacts directly and indirectly related to the construction, operation and decommissioning of the plant.

According to given standards (i.e. ISO 14040, ISO 14044[1]) the LCA is carried out in four steps:

Goal and scope definition (1): The goal of this LCA is to assess the emission of greenhouse gases and the cumulated demand of finite energy resources within the different life cycle stages, as well as throughout the whole life cycle, of geothermal power generation from low-temperature resources by means of theoretical case studies. Additionally, acidification and eutrophication effects on natural eco systems are evaluated.

The environmental effects are analyzed in reference to one kWh net power at the plant (functional unit). Net power is thereby defined as the produced gross electrical power at the generator minus the electricity consumption of the overall plant (i.e. the auxiliary power used in pumps to provide the geothermal fluid at the plant, or running the cooling devices of the power plant). Defining net power as functional unit is not representative for all running geothermal binary power plants since some countries presently pay feed-in tariffs for the produced gross power (e.g. Germany) so that the plants consume the auxiliary power from the public grid. With gross power as functional unit, the typically large auxiliary power demand of geothermal binary power plants would lead to environmental impacts that are significantly influenced by the environmental impacts of the consumed electricity mix [8]. Due to the time period considered in this study (feed-in tariffs for geothermal power production are a time-limited political instrument) and the focus on geothermal-specific aspects of an LCA, however, net power is also for these plants the more applicable functional unit.

If electricity and district heat are provided at the same site, the environmental effects are allocated between the two products so that they either refer to one kWh net power or one MJ heat at the plant. The geographic reference of this LCA is the Federal Republic of Germany. The time reference is the year 2006.

Inventory analysis (2): In this step, the mass and energy flows for all products and processes required within the overall life cycle to provide one kWh net power and, in case of the

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[1] Standard of the International Organization for Standardization: ISO 14040:2006. Environmental management – Life cycle assessment – Principles and framework; ISO 14044:2006. Environmental management – Life cycle assessment – Requirements and guidelines.

additional supply of district heat, one MJ heat are quantified. This includes, for example, the energy to operate the drilling rig (i.e. mainly diesel to run the diesel generators). The diesel fuel is produced from different types of crude oil and transported to the drill site. The use of the fuel at the drill site and the fuel provision result in airborne emissions. Since the Ecoinvent database [9], which provides life cycle data for common products (e.g. diesel) and basic processes (e.g. transportation, diesel use or waste disposal), is used for this study, only a limited number of inventory data must be assessed. For these data, however, uncertainties must be considered as they relate to an insufficient inventory data base typical for newly developing technology such as geothermal plants using enhanced low temperature reservoirs.

Mass and energy flows directly referring to the production of power and heat, respectively, are directly allocated to the corresponding energy product. Mass and energy flows related to the power conversion equipment on the surface, for example, are fully assigned to the environmental impacts of power production. Shared mass and energy flows refer to the subsurface plant part and the geothermal fluid cycle and are allocated according to the amount of exergy, which corresponds to the provided net power and district heat, respectively. The calculation of the allocation factor for power f_{el} and heat f_{th} is based on equation (1) and (2) [10].

$$f_{el} = \frac{Q_{el} w_{el}}{Q_{el} w_{el} + Q_{th} w_{th}} \qquad \text{eq. (1)}$$

$$f_{th} = \frac{Q_{th} w_{th}}{Q_{el} w_{el} + Q_{th} w_{th}} \qquad \text{eq. (2)}$$

In equation (1) and (2) Q_{el} and Q_{th} describe the total provided amount of net power and district heat, respectively, w_{el} and w_{th} the exergy content of the energy products. The exergy content of the net power equals 1 (w_{el} = 1). The exergy content of the produced heat is derived according to equation (3) from a reference ambient temperature T_a = 293.15 K and the supply and return temperature of the district heating grid T_{h1} and T_{h2}, respectively [10].

$$w_{th} = 1 - T_a \frac{\ln(T_{h1}/T_{h2})}{T_{h1} - T_{h2}} \qquad \text{eq. (3)}$$

Impact analysis (3): In order to quantify the environmental effects, all inventoried mass and energy flows are aggregated to different impact indicators according to Table 1.

Interpretation (4): The results of the impact analysis are qualitatively interpreted by separately discussing the different impact indicators. Focus is given to the influence of the different life cycle stages and the effect of data uncertainties on the life cycle performance of geothermal binary power plants typical for Europe. Due to the large range of possible plant specifications, also the impact of changing site and plant parameters is studied. In order to estimate the total range of environmental parameters associated with geothermal binary power generation, which also includes untypical plant specifications, a scenario analysis by means of “worst case” and “best case” scenarios is carried out. In order to classify all results, power related impacts are compared to the environmental key figures of a reference electricity mix and heat related impacts to a reference heat mix.

3 Definition of case studies

The environmental impacts of geothermal binary power plants are analysed by means of base cases that represent presently typical geothermal binary plants in Europe. The case study is based on a simplified plant layout and an inventory data base derived from expert surveys and the literature, which are described in the following section. Afterwards, the scope of the parameter study and the scenario analysis, which assess various geothermal binary power plants, is outlined. For the classification of the LCA results an electricity mix and a heat mix are defined as reference.

3.1 Plant concept and inventory data base

The basic plant design for providing power and, optionally, district heat from low-temperature geothermal reservoirs is shown in Figure 1. According to this plant layout, the geothermal fluid is produced from the reservoir and delivered to the surface by using a downhole pump installed in the production well. Above ground, the geothermal fluid is transported within a closed pipeline to the heat exchangers, where heat is transferred to the binary conversion cycle. Here, a low-boiling working fluid (such as an organic fluid) is preheated and evaporated. The generated vapor drives a turbine-generator unit. After the turbine, the working fluid is cooled down, condensed, and then recycled to the preheater. The condenser is charged with cooling water from a wet cooling tower. For the supply of district heat, a heat exchanger downstream of the binary unit is used. This is due to the fact that the temperature of the geothermal fluid after the heat transfer to the binary cycle is usually higher than the temperature of the working fluid vapor at the outlet of the turbine, which is in other applications typically used for the combined power and heat supply from conversion cycles. After its use, the geothermal fluid is pumped to the injection well and reinjected into the reservoir.

Back-up or peak load systems, which might be necessary at some plants providing both heat and power (the share of geothermal energy in the supply of district heat typically lies between 50 and 100 % [4], [11]), are not considered in this case study.

The life cycle information on general components of the presented plant concept (such as pipelines and heat exchangers) is derived from technical literature and data sheets. The data for common products (such as diesel, cement and steel) and basic processes (such as transports and diesel use in construction equipment) are taken from the Ecoinvent database. Geothermal-specific life cycle information (such as well drilling and completion, reservoir enhancement and the operation of the geothermal fluid cycle) is compiled in expert surveys and from the literature.

All mass and energy flows are related to plant parameters (see Appendix) in order to perform the parameter study and the scenario analysis. For analyzing data uncertainties associated with the geothermal-specific life cycle information, uncertainty factors are applied based on the expert survey and uncertainties for inventory data of geothermal heat plants surveyed in [12]. The main aspects of the inventory analysis of geothermal binary power plants are addressed in the following paragraph. The complete inventory information used in this paper are listed in the Appendix.

After the preparation of a drill site, deep wells are usually drilled in several sections using the rotary technique. A drilling section consists of the drilling itself, and the subsequent casing and cementing process. The drilling is realized by rotating the drilling rod with a drill bit at the bottom of the well. The loose rocks are removed from the well with circulating drilling mud. The amount of material and energy required to drill such wells, as well as the amount of cuttings which need to be disposed of, vary depending on the depth and diameter of the wells. Additionally, geological conditions have a strong influence because they determine the composition of the drilling mud, composition of the cement and the required thickness of the casing wall (and thus the amount of steel). On average, the amount of diesel to drive the drilling rig can roughly vary between 6 and 8 GJ per drilled meter. The amount of drilling mud required under average geological conditions ranges from 700 to 1,000 kg/m. For the completion of one meter open hole approximately 80 to 120 kg of steel for the casing and 45 to 65 kg of cement to seal the casing with the surrounding rocks is needed.

For all case studies, it is assumed that the reservoir needs enhancement measures after the wells have been completed in order to improve the permeability and hence the productivity of the reservoir. Reservoir enhancement is realized by injecting a frac fluid under high pressure into the reservoir. The energy for driving the injection pumps and the composition and amount of the frac fluid depend on the reservoir characteristics and the designated reservoir enhancement. Due to lack of experience with technically enhancing geothermal reservoirs, it is not yet possible to define representative values for energy and material flows. In this study, the reservoir enhancement is estimated with 3,000 GJ of diesel to drive the injection pumps and 260,000 m^3 water as frac fluid.

The downhole pump, pipeline and heat exchanger are the essential elements for connecting the production and injection well and transferring the geothermal heat to the binary power unit and the district heating grid. The material and energy required to install these parts is mainly determined by the flow rate of the geothermal fluid and, in the case of the pipeline, its length and the mode of construction. The material used for the heat exchangers depends on its thermal capacity.

For the binary power unit the main material input are the working fluid and system components such as heat exchangers, turbine, generator, recooling system and peripheral equipment. The required material increases with installed electrical capacity. For district heat supply, an additional heat exchanger needs to be taken into account. The binary power unit and the heat exchangers are located in a building. Material outputs due to the construction of the surface part, such as waste or emissions, are negligible and thus not considered. Regarding energy flows, the energy required to install the components at the site needs to be considered.

For plant operation, the exchange of the downhole pump and the demand for cooling water are taken into account. Furthermore, the disposal of filter residues and removed scaling is estimated. As known from the oil and gas industry, both filter residues and scaling can, depending on the site, contain small amounts of naturally occurring radioactive material (NORM). It is, therefore, assumed that about 1 to 1.4 kg/(m^3/h) filter residues and removed scaling are annually disposed of at special disposal sites. Direct gaseous pollutants are not emitted during plant operation because the geothermal fluid is transported in a closed pipeline system.

After the operational phase, the wells are filled with gravel and cement. The surface installations are disposed of or recycled.

3.2 Base cases

The plant design shown in Figure 1 is investigated in the base case analysis for two different sites. Table 2 shows the geological parameters and technical specifications of the base cases.

At site A, the geothermal reservoir is located at a depth of 3.8 km and has a temperature of 125 °C. The design flow rate of 250 m^3/h can be delivered from this reservoir with a specific power consumption in the downhole pump of 1.3 kW/(m^3/h). The power consumption depends on the pressure increase in and the efficiency of the downhole pump. The pressure increase mainly results from the geodetic difference in height between the dynamic fluid level in the production well and the surface, and the pressure required within the pipeline to avoid degassing and precipitates. Since the auxiliary power need of the downhole pump increases over-proportionally with increasing flow rate due to the reservoir characteristics at a specific site, it is assumed that the design flow rate is optimized regarding the plant's net power output [13]. The density of the geothermal fluid is assumed to 1,000 kg/m$^{3.}$

At site B, a deeper reservoir (4.7 km) with a higher temperature (150 °C) is assessed. Due to the lower productivity of this reservoir, the same specific auxiliary power input to the downhole pump results in a lower flow rate (155 m^3/h) compared to site A.

At both sites, the plants have an electrical capacity of 1.75 MW assuming a geothermal fluid temperature at the outlet of the binary cycle of 60 °C. The auxiliary power demand for the feed pump is assumed to be 10 % of the installed capacity. For the recooling of the binary cycle, an induced-draft cooling tower is assumed. The net power output resulting from the produced gross power and the auxiliary power consumed within the plant depends on the temperature and flow rate of the geothermal fluid. The plant at site B can provide more net power due to the lower flow rate and the higher temperature of the geothermal fluid, which result in a smaller auxiliary power demand.

In case of power production without an additional supply of district heat, the plants are operated with 7,000 yearly full load hours. This operation time accounts for downtime due to overhaul and maintenance and a varying power output due to changing ambient conditions. In case of the additional supply of district heat, the yearly full load hours of the power production are reduced. This reduction is because the assumed supply temperature of the district heating system (70 °C) can only be met by a geothermal fluid temperature at the outlet of the binary cycle of 77 °C. Therefore, less geothermal heat is used for power production in times of heat demand.

The net power output of the base case plants is between 6,041 and 7,679 MWh/a. In case of the additional supply of district heat, 22,349 GJ/a heat can be provided by plant B2. Plant A2, using the larger geothermal flow rate, can supply 36,00 GJ/a.

The technical life-time of both plants is assumed to be 30 years. An exchange of components with a shorter technical life-time, such as the downhole pump or the binary power unit, is taken into account.

3.3 Scope of parameter study

The plants defined in the base case analysis are not representative for all low temperature geothermal sites and plant specifications in Europe, because all assumed plant parameters may vary to a certain extent. Along with uncertainties that are generally included in theoretical evaluations of technical concepts, geothermal power generation from enhanced low temperature sites is characterized by a large range of geological preconditions. In order to analyze the influence of different parameters on the LCA results, a parameter study is carried out. The parameters, which define the base cases, are varied from minimum to maximum values. The relevant range of values is derived from existing literature and own experiences. The geothermal fluid temperature at site A, for example, will not be decreased below 98 °C because of a minimum ratio of net to gross power of 25 %. This ratio is a theoretically assumed value and represents the lower limit for geothermal binary power plants being realized from an economic viewpoint. The upper limit of the auxiliary power demand for the downhole pump is related to a minimum relevant reservoir productivity of 10 m^3/(h MPa). Sites with lower reservoir productivities are unlikely to be developed due to economic aspects. The scope of the parameter study is presented in Table 3.

3.4 “Best case” and “worst case” scenarios

In order to estimate the total range of environmental impacts for geothermal binary power generation, more than one parameter of the base case scenarios must be changed. So far, typical or representative geothermal low-temperature sites have been discussed so that in the scenario analysis sites are studied that will be exploited only by a very small number of geothermal binary power plants. Within the scenario analysis one site with exceptional geological preconditions (“best case” scenario) and one site with below-average reservoir characteristics (“worst case” scenario) are analyzed. Exceptional geological conditions are limited to a few sites, whereas sites with below-average geological conditions can be found at many places but are only exploited under specific circumstances due to economic considerations.

Building on the parameter range presented in Table 3, the above-average geothermal site (site C) is characterized by high geothermal fluid temperature, high geothermal temperature gradient, high specific heat capacity of the fluid, and long technical life-time of the reservoir (Table 4). A flow rate of 500 m^3/h is obtained from the reservoir with small pumping effort. Regarding the site with below-average geological preconditions (site D), opposite parameter assumptions are made. However, a minimum ratio of net to gross power of 25 % is assumed as restriction. As mentioned above, this ratio should represent the economic lower limit for geothermal binary power plants being realized.

At both sites, power production as well as combined power and heat production with average specifications regarding the surface plant part are analyzed (plant C1, C2, D1 and D2). In order to show the effect of different surface installations at the sites, different technical specifications are assumed in further scenarios. Less efficient surface technology is analyzed for site C (plant C1- and C2-). At site D, the influence of improved plant design is investigated (plant D1+ and D2+).

3.5 Reference electricity mix and reference heat mix

For the classification of the environmental impacts within the energy sector, the power related LCA results are compared to the environmental key figures of a reference electricity mix shown in Table 5. This reference mix represents a business-as-usual development until 2010 [6]. The heat related impacts are compared to a reference heat mix that is based on a mix of single combustion applications [6].

4 Results

4.1 Base case analysis

The plants that provide electrical power (plant A1 and B1) have larger impacts for all analyzed impact categories compared to the plants that provide both power and heat (plant A2 and B2, Figure 2). Comparing the power providing plants, plant B1 shows slightly lower environmental key figures. This means that the larger energy and material flows for assessing the deeper reservoir at site B are made up for by the higher net power output (cf. Table 2). Among the plants that provide power and heat, plant A2 has lower power and lower heat related environmental impacts compared to plant B2 due to the larger geothermal fluid flow rate and the hence higher amount of supplied district heat.

Considering the uncertainties related to the inventory analysis of geothermal binary power plants, the impacts can range from about 79 to 121 % of the indicated values. Since many data are characterized by an assumed uncertainty factor of +/- 5 %, the influence of highly uncertain data, such as the data for constructing the subsurface plant part, is predominant (cf. Appendix).

The construction of the underground plant components causes for all plants more than 80 % of the analyzed environmental impacts (Figure 2) and has the largest influence of all life cycle stages. The influence is larger for site B because of the larger effort for locking up the deeper reservoir.

The environmental impact resulting from constructing the subsurface part is dominated by the energy required for drilling the wells (Figure 3). This is true especially regarding the PO_4^{3-}-equivalent, because the energy for drilling is based on diesel consumption in construction equipment (see Appendix), which results in comparatively large PO_4^{3-}-equivalent emissions. The PO_4^{3-}-equivalent, however, is probably lower than calculated because the diesel utilization in the drilling equipment is more efficient than that of the machine park implemented in the Ecoinvent database, which typically represents a large bandwidth of stationary and mobile construction machines.

The influence of the casing material (i.e. steel) depends on the impact category and is most significant for the CED and the CO_2-equivalent. By contrast, the influence of the material- and energy-input for reservoir enhancement is remarkably lower for these categories. Only for the PO_4^{3-}-equivalent is the contribution of the enhancement in the same order of magnitude as the casing.

In contrast to the construction of the subsurface components, the construction of the above ground facilities contributes only 2 to 11 % of the total environmental impacts (Figure 2). Evaluating the power related impacts, about 60 % of the impact caused by the construction of the surface components is related to the geothermal fluid cycle and about 40 % is caused by the binary power unit. The heat related environmental impacts due to surface construction are mainly related to the geothermal fluid cycle.

The operational phase is responsible for less than 0.4 % of the environmental effects, mainly due to replacement of the downhole pump (Figure 2). The plant decommissioning has a negligible effect on the analyzed environmental impacts.

4.2 Parameter study

The general behavior of environmental impacts to changing parameters shown in Figure 4 for the example of the power related CO_2-equivalent of plant A2 is applicable for all plant concepts and impact indicators. In order to indicate differences in the extent of impact changes, the CO_2-equivalents of all plants are additionally plotted for single points of the parameter variation. Figure 5 shows the maximum deviations from the base case impacts by using the minimum and maximum values of each parameter (cf. Table 3). Figure 6 gives an overview on the sensitivity of the life cycle calculations to changing parameters by using small deviations from the base case parameters (i.e. a deviation of +/- 5%).

In Figure 5 it can be seen that a reduction of the analyzed impacts to less than 50 % of the reference value but also an increase by a multiple is possible. The sensitivity analysis shows that small parameter changes mainly cause impact variations by +/- 9% (Figure 6).

A changing reservoir or geothermal fluid temperature at constant well depth has the largest effect on the impact indicators (Figure 4). An increasing temperature reduces the environmental impacts due to the increase in net power output resulting from an improvement of the conversion efficiency. A decreasing reservoir temperature, which leads to increasing impacts, has a stronger effect compared to an increasing temperature. The effect of temperature changes on the LCA results gets stronger for lower reservoir temperatures (Figure 5). At the same site, the impacts of plants that provide power (plant A1 and B1) are more sensitive to changing reservoir temperatures than plants that provide both power and heat (plant A2 and B2) since the production of district heat is not affected (Figure 6).

Regarding other reservoir parameters, the effect of varying plant life on the LCA results is in the same order of magnitude as for a changing reservoir depth at constant reservoir temperature. The specific heat capacity of the geothermal fluid causes comparatively small maximum impact changes (Figure 5). The sensitivity of the LCA results on this parameter, however, is significant (Figure 6).

Increase of the geothermal fluid flow rate (pumped with the same relative pumping power due to increasing reservoir productivity) has a reducing effect on the LCA results (Figure 4). An increasing auxiliary power demand of the downhole pump (producing a constant flow rate due to decreasing reservoir productivity), increases the environmental impacts (Figure 4). This effect is more significant at sites that produce large flow rates and for plants that provided only power (Figure 5).

The maximum effect of variations in binary cycle parameters is smaller than the influence of variations in either reservoir or geothermal fluid cycle parameters (Figure 5). The sensitivity of the analyzed environmental impacts, in contrast, is in some cases more significant (Figure 6). Changing conversion efficiency has a stronger effect on the LCA results at sites with lower reservoir temperatures. Even though changes of the binary cycle parameters do not influence the district heat production, heat and power related key figures are affected by parameter changes to the same extent (Figure 5) since the allocation of the absolute environmental impacts is shifted towards the power production.

The variation of the district heat parameters, in contrast, has less influence on the power related impacts than on the heat related key figures (Figure 5). The largest effect on the power related impacts is caused by a variation of the thermal full load hours (Figure 4). The strongest sensitivity of the LCA results, which is generally small for the district heat parameters, is on changes of the return temperature (Figure 6). Variation of supply temperature has a negligible effect on the power related impacts. Increasing supply temperatures, for example, lead to a reduction of the net power supply. This influence on the power production is, however, made up for by shifting the allocation of the absolute impacts towards the heat production since the amount of supplied heat remains constant (assuming a constant temperature spread in the district heating grid). Regarding the heat related impacts, a remarkable reduction of the environmental key figures results from high thermal full load hours and low supply and return temperatures (Figure 5). The heat related LCA results are most sensitive on the supply temperature due to the influence on the provided amount of heat and the exergetic factor (Figure 6).

4.3 Scenario analysis

The results of the scenario analysis (Figure 7) cover a large range of environmental impacts. The site with above-average geological conditions (site C) represents the lower limit of environmental impacts associated with geothermal binary power plants. For average surface technology installed at this site (plant C1 and C2), the LCA results are about 85 % lower compared to the base cases (plant A1, B1 and A2, B2, respectively). Even if less efficient surface equipment is used at site C (plant C1- and C2-), the environmental impacts are still about 80 % lower.

The site with below-average geological conditions (site D) represents the upper limit of life cycle impacts associated with geothermal binary power production. With average plant technology (plant D1), this site leads to environmental impacts that exceed the values of the base case plants A1 and B1 by a multiple. If power and heat are provided with average equipment, the environmental impacts can be reduced. Plant D2, however, still exceeds the environmental key figures of plant A2 and B2 by factor 10. If high-efficiency surface technology is installed at site D (plant D1+), impact indicators about 3 times higher than the base case results are achieved. In case district heat can be additionally supplied to a district heating grid with a continuous heat demand and a very low return temperature (plant D2+), the environmental impacts exceed the base cases figures by factor 2.

4.4 Comparison to electricity mix and heat mix

The results of the base case and the scenario analysis are in Figure 8 compared to the environmental impacts of the reference mixes. Regarding the power related impacts, CO_2-equivalent and CED of the geothermal binary power plants are below the key figures of the reference mix, except the power production based on average technology at the site with below-average geological conditions (plant D1). Typical geothermal binary power plants, represented by plant A1, A2, B1 and B2, have a CED and CO_2-equivalent that are about 6 to 11 % that of the reference mix, uncertainties in the inventory data of the geothermal binary power production included. At the site with above-average geological conditions (site C), CO_2-equivalent and CED can reach below 1 % of the reference values. At the site with below-average conditions (site D), environmental advantages regarding CO_2-equivalent and CED (i.e. 40% and less compared to the reference impacts) are only achieved with the use of high-efficiency surface technology.

Comparing the power related SO_2-equivalents significantly lower impacts than the electricity mix are only achieved at sites with at least average geological preconditions. Regarding the PO_4-equivalents, in contrast, geothermal binary power plants result in significantly lower impacts only at sites with above-average geological characteristics. For the comparison of the PO_4-equivalents, however, the applicability of the Ecoinvent data must be considered (cf. section 4.1). Diesel use in drilling equipment, which causes the main part of the PO_4^{3-}-equivalent, is probably more efficient than assumed for the average construction machine in the Ecoinvent data base. Therefore, also the PO_4^{3-}-equivalent of geothermal binary power generation is probably lower than indicated in this study.

A comparison of the heat related impacts shows that at sites with average geological conditions and better, the impact indicators of heat from geothermal binary power plants that provide both power and heat are significantly lower than the key figures of the reference heat mix. At sites with below average geological characteristics, only high-efficiency surface technology leads to lower impacts compared to the heat mix.

5 Conclusions

This paper evaluates greenhouse gas emissions, consumption of finite energy resources and SO_2- and PO_4^{3-}-equivalent emissions during the life cycle of geothermal binary power plants. The results show that geothermal binary power plants cannot be described by representative environmental key figures due to the wide range of geological site preconditions, different plant set-ups and data uncertainties, which are typical for theoretical evaluations of complex technical concepts not yet established on the market. Based on the results general conclusions, however, can be drawn:

- The life cycle of geothermal binary power plants is characterized by large material and energy inputs, especially during construction of the subsurface plant part. Successful exploration and access to the reservoir with minimum drilling and completion efforts referring to a specific site is hence the precondition for low environmental impacts.
- Due to the large influence of the auxiliary power required for delivering the geothermal fluid from the reservoir on the net power output, a sufficient reservoir productivity is required in order to make up for the large material and energy inputs during construction. The enhancement of the reservoir productivity by means of technical measures is, therefore, a key aspect for the improvement of the environmental performance of geothermal binary power plants.
- The surface plant part is determining for the efficient use of the geothermal heat. Regarding an optimum net power output at a specific site, not only high conversion efficiency of the binary power unit but also low auxiliary power for recooling are important factors for the environmental performance.
- Geothermal binary plants offer a large potential to provide power and heat from the same plant, and the supply of district heat significantly improves the environmental key factors. The possibility to supply heat is, however, based on an adequate heat customer structure that needs to be developed at the beginning of a geothermal power plant project.

Comparing geothermal binary power plants to the environmental key figures of a reference electricity and a reference heat mix shows that sites with above average and average conditions have significantly lower emissions of CO_2-equivalent pollutants, a significantly lower consumption of finite energy resources and lower SO_2-equivalent emissions. PO_4-equivalent emissions are significantly lower only at sites with above average geological conditions. For typical sites, assured conclusions regarding PO_4-equivalent emissions can only be drawn after further investigations due to uncertainties with the used life cycle data base.

Less favorable geothermal sites can also be realized with greenhouse gas emissions and consumption of finite energy resources that are significantly below the values of the reference mix. The precondition is adequate design of the surface facilities (i.e. high-efficiency technology and continuous supply of district heat). Referring to SO_2- and also PO_4^{3-}-equivalent emissions, lower impacts cannot always be achieved at these sites so that a detailed and site-specific environmental analysis including all relevant options of energy supply must be carried out for proper decision making.

If the aspects addressed above are taken into consideration, geothermal heat and power generation from low-temperature resources can make a large contribution to a more sustainable energy system today and in the future.

Acknowledgement

This paper is based on the results of a research project carried out by the Institute for Energy and Environment, Leipzig (Germany) for the German Federal Environment Agency (UBA). We would like to thank UBA for the financial support and Christiane Lohse (UBA) especially for the constructive collaboration. For further active support regarding the content, we would like to thank Martin Karad and Robert Huelke from MI Swaco, Axel Sperber from IDEAS and Reinhard Jung formerly from the GGA Institute.

Appendix

The data, which has been used in the Ecoinvent data base for the inventory analysis of the analyzed geothermal binary power plants, are summarized in Table 6 for plant construction, in Table 7 for plant operation and in Table 8 for decommissioning of the plants.

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Figure Captions

Figure 1: Plant design and system boundaries of the analysed geothermal binary power plants exploiting a low-temperature reservoir for the supply of net power and, optionally, district heat

Figure 2: Results of the base case analysis showing the environmental impact indicators of typical geothermal binary power plants, their break down referring to the different life cycle stages and the influence of inventory data uncertainties

Figure 3: Typical break down of the environmental impacts caused by subsurface construction for the example of plant A1

Figure 4: Parameter study for the example of plant A2 showing the general behavior of the analyzed environmental impacts to changing parameters

Figure 5: Parameter study for the example of the CO_2-equivalent showing the general differences in impact changes for all plants using minimum and maximum parameters

Figure 6: Parameter study for the example of the CO_2-equivalent showing the general differences in impact changes for all plants using small parameter changes

Figure 7: Results of the scenario analysis showing the environmental impact indicators of geothermal binary power plants at untypical sites, such as a site with above-average and a site with below-average geological conditions (site C and D, respectively)

Figure 8: Comparison of the base case and scenario analysis results to the reference electricity and reference heat mix

Tables

Table 1: Impact indicators and conversion factors for the analyzed environmental effects [9]

Environmental effect	Impact indicator	Inventoried inputs / outputs	Conversion factors
Demand of finite energy resources	CED [a]	crude oil	1 MJ/MJ
		hard coal	1 MJ/MJ
		lignite	1 MJ/MJ
		natural gas	1 MJ/MJ
		nuclear power [b]	10,908 MJ/kWh
Global warming	CO_2-equivalent [c, d]	CO_2	1 kg_E/kg_P
		CH_4	23 kg_E/kg_P
		N_2O	296 kg_E/kg_P
		SF_6	22,200 kg_E/kg_P
		CF_4	5,700 kg_E/kg_P
		C_2F_6	11,900 kg_E/kg_P
Acidification	SO_2-equivalent [d]	SO_x as SO_2	1 kg_E/kg_P
		NO_x as NO_2	0.7 kg_E/kg_P
		NH_3	1.88 kg_E/kg_P
		HCl	0.88 kg_E/kg_P
		HF	1.6 kg_E/kg_P
		H_2S	1.88 kg_E/kg_P
Eutrophication	PO_4^{3-}-equivalent [d]	NO_x as NO_2	0.13 kg_E/kg_P
		NH_3	0.35 kg_E/kg_P

[a] Cumulated Energy Demand (CED) referring to lower heating values. [b] Net electricity from nuclear power plants. [c] Time horizon 100 years. [d] Subscripts: E equivalent, P pollutant.

Table 2: Geological and technical parameters of the base case plants referring to the plant concept in Figure 1

Parameter	Unit	Site A		Site B	
Reservoir					
Reservoir depth	km	3.8		4.7	
Reservoir / geothermal fluid temperature	°C	125 [a]		150 [a]	
Specific heat capacity geothermal fluid	kJ/(kg K)	4		4	
Technical life-time	a	30 [b]		30 [b]	
Geothermal fluid cycle [c]					
Geothermal fluid flow rate	m^3/h	250 [d]		155 [d]	
Auxiliary power need downhole pump	MW_{el}	0.33 [e]		0.20 [e]	
		Plant A1	Plant A2	Plant B1	Plant B2
Binary cycle					
Conversion efficiency	%	9.7 [f]	9.7 [f]	11.2 [f]	11.2 [f]
Geothermal fluid outlet temperature	°C	60 [g]	60 [g]/77 [g]	60 [g]	60 [g]/77 [g]
Installed power capacity	MW	1.75 [h]	1.75 [h]	1.75 [h]	1.75 [h]
Full load hours	h/a	7,000	6,529 [i]	7,000	6,662 [i]
Auxiliary power need feed-pump	MW_{el}	0.18 [j]	0.18 [j]	0.18 [j]	0.18 [j]
Auxiliary power need recooling	MW_{el}	0.33 [k]	0.33 [k]	0.28 [k]	0.28 [k]
Cooling water demand	m^3/h	49 [k]	49 [k]	42 [k]	42 [k]
District heat supply [l]					
Supply temperature	°C		70		70
Return temperature	°C		50		50
Thermal full load hours	h/a		1,800		1,800
Installed thermal capacity	MW_{th}		5.56 [m]		3.45 [m]
Net power output	GMWh/a	6,476	6,041	7,679	7,308
District heat supply	GJ/a		36,000		22,349

[a] Calculated from reservoir depth, an average geothermal temperature gradient of 0.03 k/m and an assumed surface temperature of 10 °C. [b] Based on experience; components with a shorter technical life-time: down-hole pump 4 a, other components in the geothermal fluid cycle and the binary power unit 15 a. [c] Assumed pipeline length 1,500 m. [d] Values assumed to be optimum flow rate regarding maximum net power output; density of the geothermal fluid1,000 kg/m^3. [e] Geothermal fluid circulation with downhole pump; calculation of power demand based on an estimated specific auxiliary power demand relating to fluid flow rate of 1.3 kW/(m^3/h) based on [16]. [f] Estimated efficiency at design point depending on geothermal fluid temperature based on [15]. [g] Estimated value based on experience; higher temperatures at times of heat supply according to an assumed temperature difference between geothermal fluid and district heating grid of 7 K. [h] Calculated from geothermal heat input and conversion efficiency. [i] Calculated full load hours due to reduction in power production at times of district heat supply. [j] Relative auxiliary power demand of 10 % relating to installed capacity based on [15]. [k] Induced-draft cooling tower with specific auxiliary power demand relating to waste heat of 20 kW_{el}/MW_{th} and a specific cooling water demand relating to waste heat of 3 $m^3/h/MW_{th}$ based on [17]. [l] District heating grid supplied to 100 % by geothermal heat. [m] Calculated from geothermal fluid temperature after binary cycle, fluid flow rate, heat capacity and cooling of geothermal fluid down to 57 °C.

Table 3: Scope of the parameter study

Parameter	Unit	Value range
Reservoir		
Reservoir depth	km	2.9…5.8 (site A) [a]; 3.5…7.0 (site B) [a]
Reservoir / geothermal fluid temperature	°C	98…163 (site A) [b];104…197 (site B) [b]
Specific heat capacity geothermal fluid	kJ/(kg K)	3.5…4.2 [c]
Technical life-time	a	20…40 [d]
Geothermal fluid cycle		
Geothermal fluid flow rate	m^3/h	100…500 [e]
Specific auxiliary power need relating to fluid flow rate	kW/(m^3/h)	0.5…3.0 [f]
Binary cycle		
Conversion efficiency	%	7.7…11.7 (site A) [g]; 9.3…13.2 (site B) [g]
Auxiliary power feed pump	%	9…11 [h]
Geothermal fluid outlet temperature	°C	50…70 [h,i]
Full load hours	h/a	6,000…8,000 [j,i]
Auxiliary power need recooling relating to waste heat	kW$_{el}$/MW$_{th}$	5…35 [k]
Cooling water demand relating to waste heat	m^3/h/MW$_{th}$	1.5…4.5 [k]
District heat supply		
Thermal full load hours	h/a	0…7,000 [l]
Supply temperature	°C	50…90 [m]
Return temperature	°C	30…60 [n]

[a] Reservoir temperature is kept constant and the geothermal temperature gradient is varied between 0.02 and 0.04 K/m. [b] Reservoir depth is kept constant and the geothermal temperature gradient is varied between 0.02 and 0.04 K/m for site B and between 0.023 and 0.04 K/m for site A because of a minimum assumed net power output of 25 % referring to the produced gross power. [c] Lower and upper value correspond to a very high and a very low mineral content of the geothermal fluid. [d] Relevant range of values for the operation of properly designed and managed geothermal reservoirs. [e] Relevant range of values based on existing geothermal binary power plants; values refer to optimum flow rates regarding maximum net power output; increasing flow rates hence refer to an increasing reservoir productivity; density of the geothermal fluid1,000 kg/m^3. [f] Range of values based on an expected reservoir productivity of 10 to 100 m^3/(h MPa) and technical restrictions associated with the use of downhole pumps. [g] Relevant deviation +/- 2 %-points from the base case values based on [18]. [h] Based on [15]. [i] Referring to design point. [j] Lower and upper value correspond to smaller or larger variations of ambient conditions during the year. [k] Based on [17]. [l] Upper value corresponds to improved heat customer structure. [m] Assuming a constant temperature spread in the heating grid. [n] Assuming a constant supply temperature in the heating grid.

Table 4: Geological and technical parameters of the plants for the scenario analysis based on the parameter assumptions and calculations in Table 2 and 3

Parameter	Unit	Site C				Site D			
Reservoir									
Reservoir depth	km	4.8 [a]				5.0 [b]			
Geothermal fluid temperature	°C	200				110			
Specific heat capacity geoth. fluid	kJ/(kg K)	4.2				3.8			
Technical life-time	a	40				20			
Geothermal fluid cycle									
Geothermal fluid flow rate	m^3/h	500				100			
Auxiliary power need downhole pump relating to fluid flow rate	kW/(m^3/h)	0.5				2.0			
		Plant C1	Plant C2	Plant C1-	Plant C2-	Plant D1	Plant D2	Plant D1+	Plant D2+
Binary cycle									
Conversion efficiency	%	13.6	13.6	11.6	11.6	8.6	8.6	10.6	10.6
Geothermal fluid outlet temperature	°C	60	60 / 77 [c]	70	70 / 77 [c]	60	60 / 77 [c]	50	50 / 77 [c]
Installed power capacity	MW	11.10	11.10	8.79	8.79	0.46	0.46	0.67	0.67
Full load hours	h/a	7,000	6,781	6,000	5,903	7,000	5,903	8,000	6,388
Auxiliary power need feed-pump	%	10	10	11	11	10	10	9	9
Auxiliary power need recooling relating to waste heat	kW_{el}/MW_{th}	20	20	30	30	20	20	5	5
Cooling water demand relating to waste heat	$m^3/h/MW_{th}$	3	3	4.5	4.5	3	3	1.5	1.5
District heat supply									
Supply temperature	°C		70		70		70		70
Return temperature	°C		50		50		50		30
Thermal full load hours	h/a		1,800		1,800		1,800		7,000
Installed thermal capacity	MW		11.67		11.67		2.11		4.22
Net power output	MWh/a	58,2876	56,456	33,354	32,815	799	729	3,081	1,868
District heat supply	GJ/a		75,600		75,600		13,680		106,400

[a] Geothermal temperature gradient 0.04 K/m. [b] Geothermal temperature gradient 0.02 K/m. [c] Higher temperatures at times of heat supply.

Table 5: Environmental impact indicators for the reference electricity mix and reference heat mix

Impact indicator	Electricity mix [a]	Heat mix [b]
CO_2-equivalent	566 g/kWh_{el}	81.5 g/MJ_{th}
CED	8.91 MJ/kWh_{el}	1.23 MJ/MJ_{th}
SO_2-equivalent	1,083 mg/kWh_{el}	115 mg/MJ_{tj}
PO_4^{3-}-euqivalent	59.9 mg/kWh_{el}	7.7 mg/MJ_{th}

[a] Breakdown of provided net electricity according to [6], [14]: 26 % lignite coal, 26 % nuclear power, 24 % hard coal, 12 % natural gas, 4 % hydropower, 4 % wind power, 1 % crude oil, 3 % other fuels. [b] Breakdown of single combustion heat mix according to [6]: 54 % natural gas condensing boilers, 46 % oil boilers.

Table 6: Mass- and energy flows for the construction of geothermal binary power plants

	Type	Description	Quantity	Unit	Uncertainty factor in %
Drilling site preparation	Input	Diesel in construction equipment	20,000[a.b]	MJ per site	-/+5[k]
	Input	Cement, unspecified	300[a]	kg per drilling site	-/+5[k]
Drilling rig drive	Input	Diesel in construction equipment	7,492[c]	MJ/m per well	-/+20[c,k]
Drilling mud	Input	Diesel in construction equipment	181.3[d]	MJ/m per well	-/+20[d,k]
	Input	Bentonite	7.7[d]	kg/m per well	-/+20[d,k]
	Input	Inorganic chemicals	6.7[d]	kg/m per well	-/+20[d,k]
	Input	Starch	12.8[d]	kg/m per well	-/+20[d,k]
	Input	Chalk	5.4[d]	kg/m per well	-/+20[d,k]
	Input	Water, decarbonized	671.4[d]	kg/m per well	-/+20[d,k]
	Input	Calcium carbonate	6.7[d]	kg/m per well	-/+20[d,k]
	Output	Disposal of drilling cuttings	456.0[d]	kg/m per well	-/+5[d,k]
Casing	Input	Steel, low alloyed	69.1[c.e]	kg/m per well	-/+20[c,k]
	Input	Steel, high alloyed	34.0[c.e]	kg/m per well	-/+20[c,k]
Cementation	Input	Bentonite	0.2[c]	kg/m per well	-/+20[c,k]
	Input	Inorganic chemicals	0.4[c]	kg/m per well	-/+20[c,k]
	Input	Portland limestone cement	23.5[c]	kg/m per well	-/+20[c,k]
	Input	Silica sand	7.0[c]	kg/m per well	-/+20[c,k]
	Input	Cement, unspecified	7.3[c]	kg/m per well	-/+20[c,k]
	Input	Water, decarbonized	16.9[c]	kg/m per well	-/+20[c,k]
Reservoir enhancement	Input	Diesel in construction equipment	3,000[f]	GJ per well	-/+40[g]
	Input	Water. desalinated	260,000[f]	t per well	-/+40[g]
Transport (subsurface construction)	Input	Trucking (32 t)	144,000[g]	tkm per well	-/+5[k]
	Input	Rail transport	413,000[g]	tkm per well	-/+5[k]
Geothermal fluid cycle	Input	Steel, high alloyed	93.6[e,g]	kg/(m^3/h)	-/+5[k]
	Input	Steel, low alloyed	189.9[e,g]	kg/(m^3/h)	-/+5[k]
	Input	Diesel in construction equipment	7.6[e]	MJ/m	-/+5[k]
	Input	Trucking (32 t)	40[g]	km	-/+5[k]
	Input	Rail transport	405[g]	km	-/+5[k]
Heat exchanger (binary unit)	Input	Steel, high alloyed	7[h]	kg/kW_{th}	-/+5[k]
Binary plant unit	Input	Organic chemicals	0.3[g]	kg/kW_{el}	-/+20[k]
	Input	Steel, low alloyed (cooling tower)	1,500[l]	kg/MW_{th}	-/+10[k]
	Input	Steel, low alloyed (other components)	37.8[g,e]	kg/kW_{el}	-/+10[k]
	Input	Copper	1.2[g,i]	kg/kW_{el}	-/+10[k]
	Input	Trucking (32 t)	50[j]	km	-/+10[k]
	Input	Rail transport	2,000[j]	km	-/+10[k]
Plant building	Input	Concrete	16[j]	m^3	-/+5[k]
	Input	Steel, low alloyed	1,250[j]	kg	-/+5[k]
	Input	Trucking (32 t)	40[j]	km	-/+5[k]
	Input	Rail transport	40[j]	km	-/+5[k]
Heat exchanger (district heat supply)	Input	Steel, high alloyed	7[h]	kg/kW_{th}	-/+5[k]
Installation surface part	Input	Diesel in construction equipment	1,000[a]	MJ	-/+5[k]

[a] [24]; [b] [25]; **[c]** [20]; **[d]** [21]; **[e]** based on [23], Teil XIV, p. 47 assuming that 33 % of total steel amount is high alloyed material, 67 % are low alloyed; **[f]** [22]; **[g]** [3], p. 93-94; [h] [23], Teil XIV, p. 34; [i] based on [23], Teil XIV, p. 27 assuming that 30 % of total steel amount is copper, 70 % is low alloyed low alloyed material; [j] [23]. Teil XIV, p. 45; [k] assumption based on [12]; [l] based on http://www.rehsler-kuehlsysteme.de/pdf/Flyer-Kuehlturm.pdf

Table 7: Mass- and energy-flows during operation of geothermal binary power plants

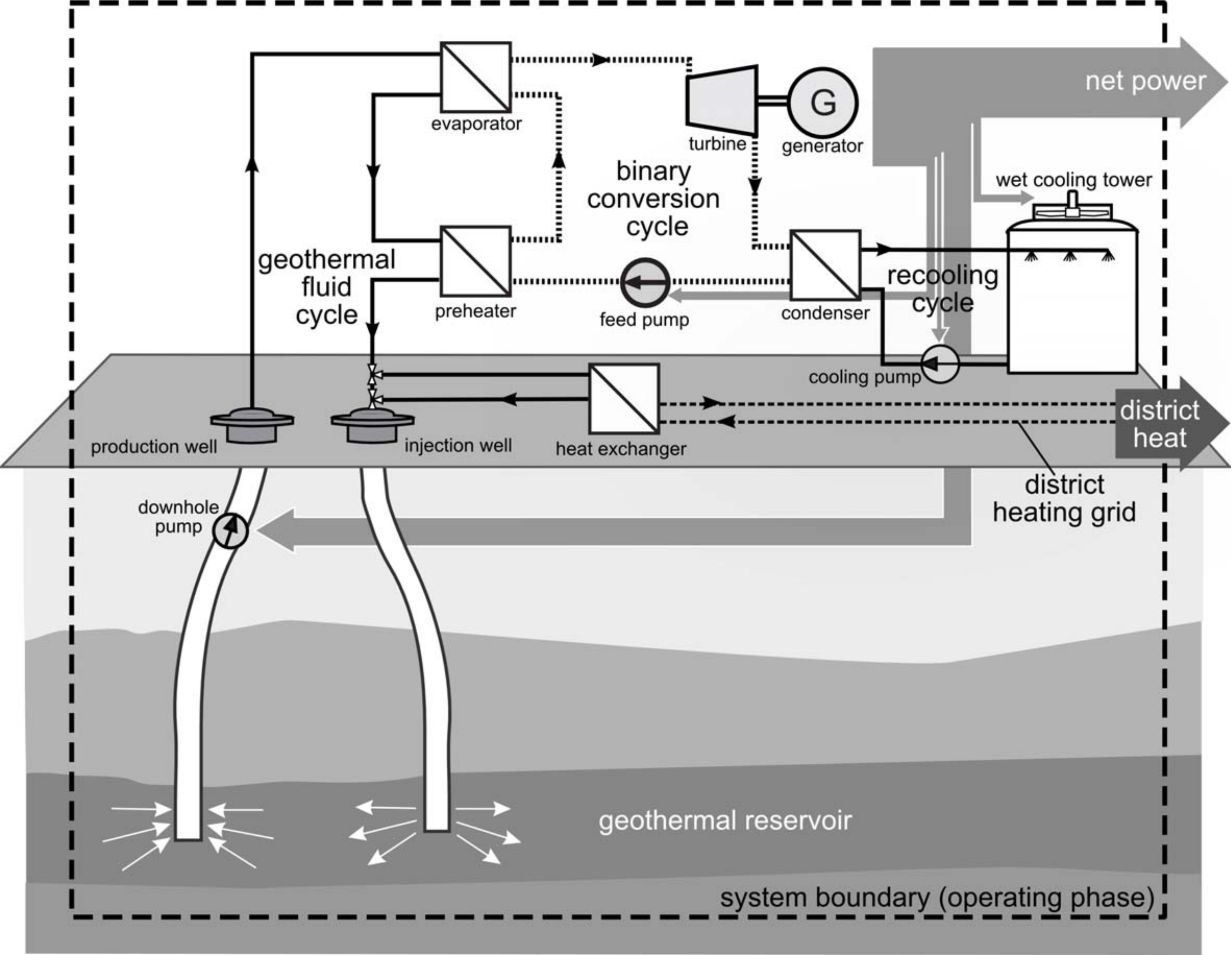
	Type	Description	Quantity	Unit	Uncertainty factor in %
Exchange downhole pump	Input	Steel, high alloyed	4.5[a]	t/a	-/+20[c]
	Output	Disposal of steel	4.5[a]	t/a	-/+20[c]
	Input	Trucking (32 t)	250[a]	tkm/a	-/+20[c]
Disposal filter residues and scaling	Output	Disposal of hazardous waste	1.5[b]	$\mathrm{kg/a/(m^3/h)}$	-/+20[c]
Operation binary plant	Input	Water, decarbonized	3	$\mathrm{m^3/h/MW_{th}}$	-/+5[c]

[a] [3], p. 93-94; [b] own estimations, filter capacity approx. 5 kg; [c] assumption based on [12];

Table 8: Mass- and energy flows for decommissioning of geothermal binary power plants

	Type	Description	Quantity	Unit	Uncertainty factor in %
Dismantling subsurface	Input	Gravel	51.1[a.b]	kg/m per well	-/+5[a,d]
	Input	Cement, unspecified	4.9[a.b]	kg/m per well	-/+5[a,d]
Dismantling surface	Input	Disposal of building, partial recycling	19[c]	t	-/+5[d]
	Input	Disposal of copper, shredder-material	2.4[c]	$\mathrm{kg/kW_{el}}$	-/+5[d]
	Input	Disposal of steel	567[c]	$\mathrm{kg/(m^3/h)}$	-/+5[d]
	Input	Disposal of steel	75.6[c]	$\mathrm{kg/MW_{el}}$	-/+5[d]
	Input	Disposal of hazardous waste	600[c]	$\mathrm{kg/MW_{el}}$	-/+5[d]

[a] [20]; [b] [3], p. 93-94; [c] according to material amounts for surface plant part in Table 6 considering shorter plant life of surface equipment; [d] assumption based on [12];


evaporator
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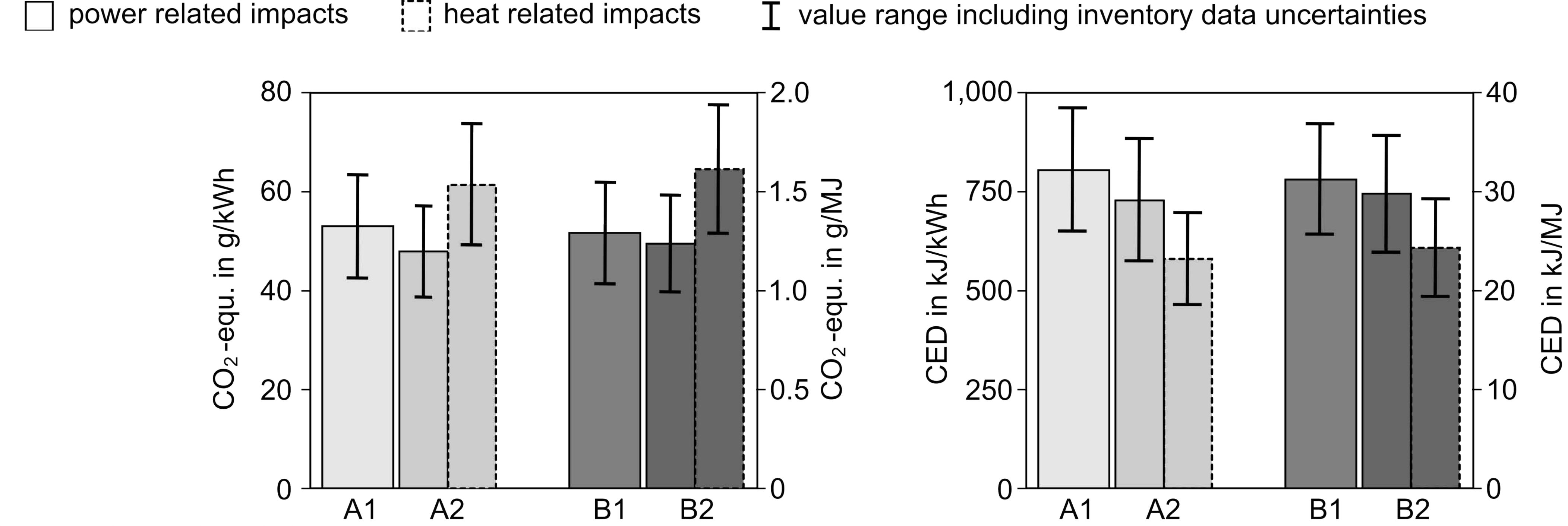
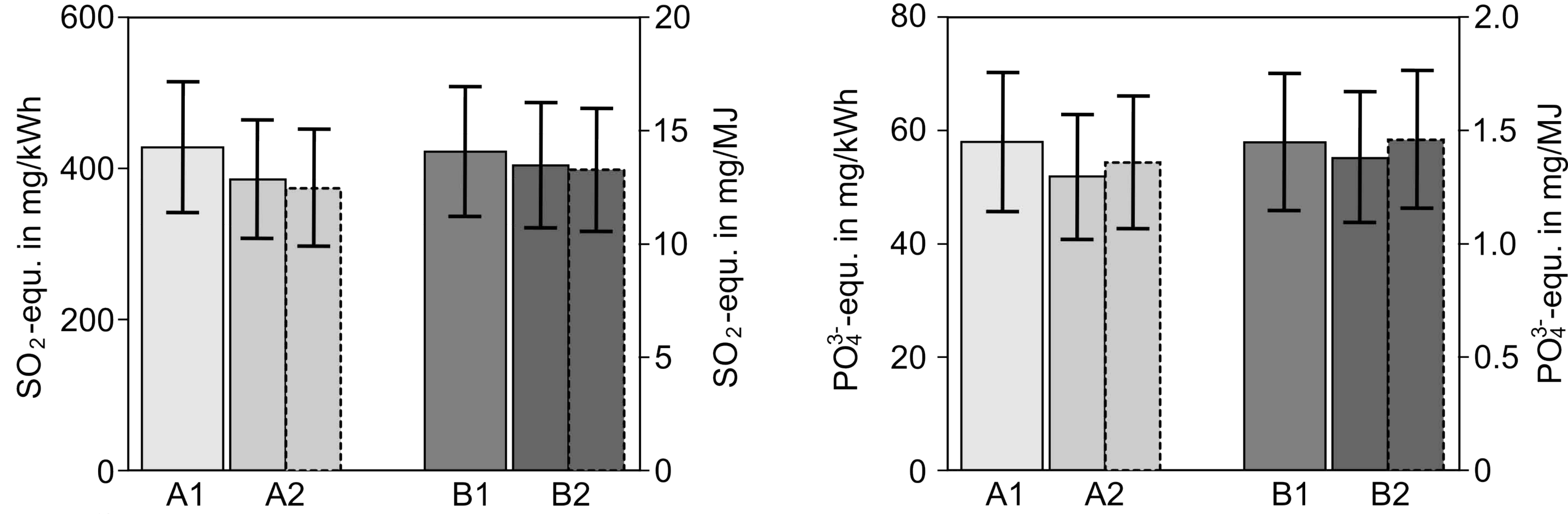
geothermal fluid cycle
preheater
feed pump
condenser
recooling cycle
cooling pump
production well
injection well
heat exchanger
district heat
district heating grid
downhole pump
geothermal reservoir
system boundary (operating phase)



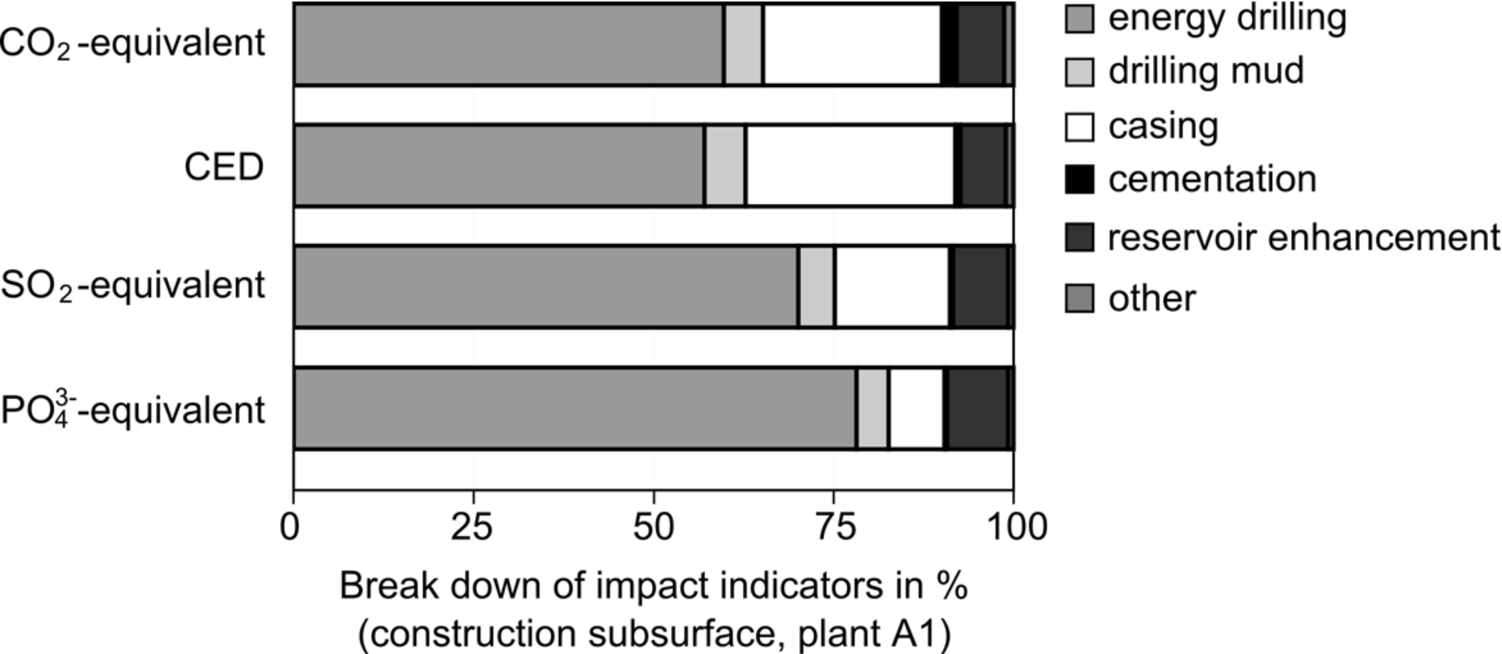
break down of impact indicators in %

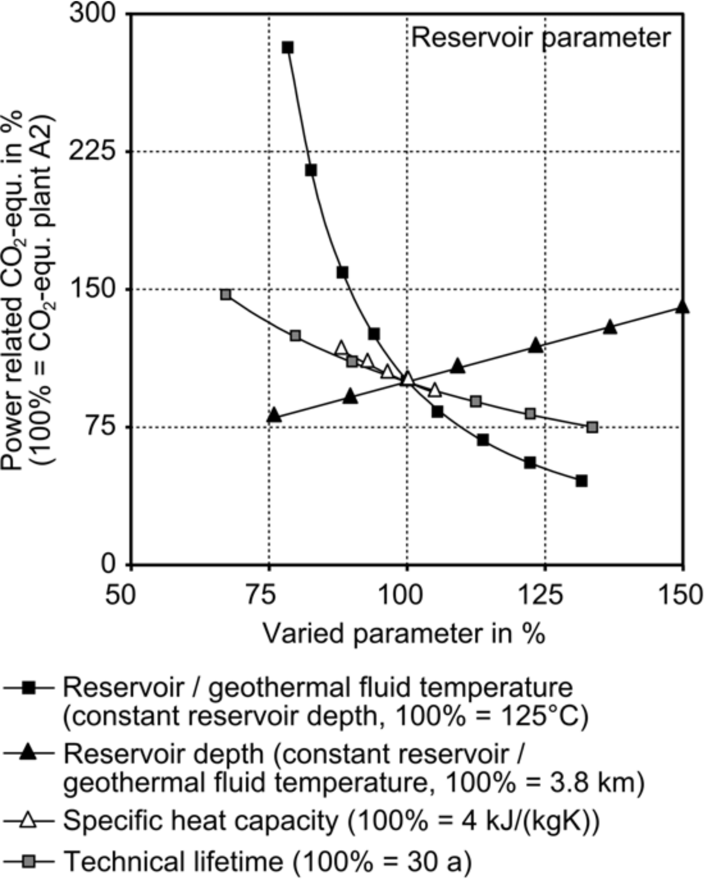
construction subsurface	88.1	87.2	90.6	91.9	91.5	93.3	86.9	85.9	89.3	91.1	90.7	92.4
construction surface	9.1	9.9	7.3	5.8	6.1	4.9	10.5	11.3	8.5	6.7	7.1	5.7
operation	2.5	2.6	1.8	2.0	2.1	1.5	2.5	2.6	2.1	2.1	2.1	1.7
decomissioning	0.3	0.3	0.3	0.3	0.3	0.3	0.1	0.1	0.1	0.1	0.1	0.2

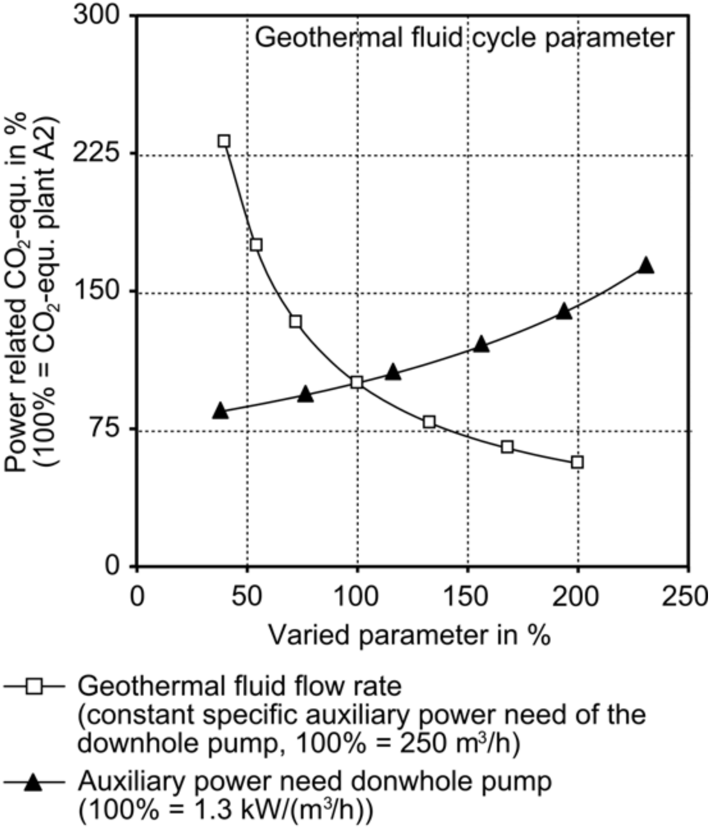


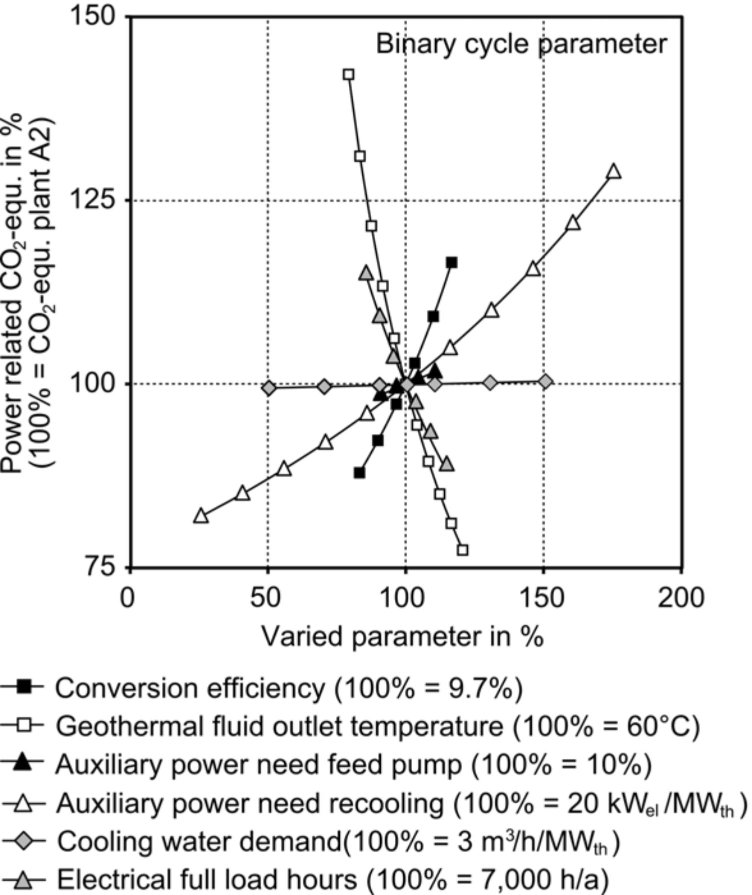
break down of impact indicators in %

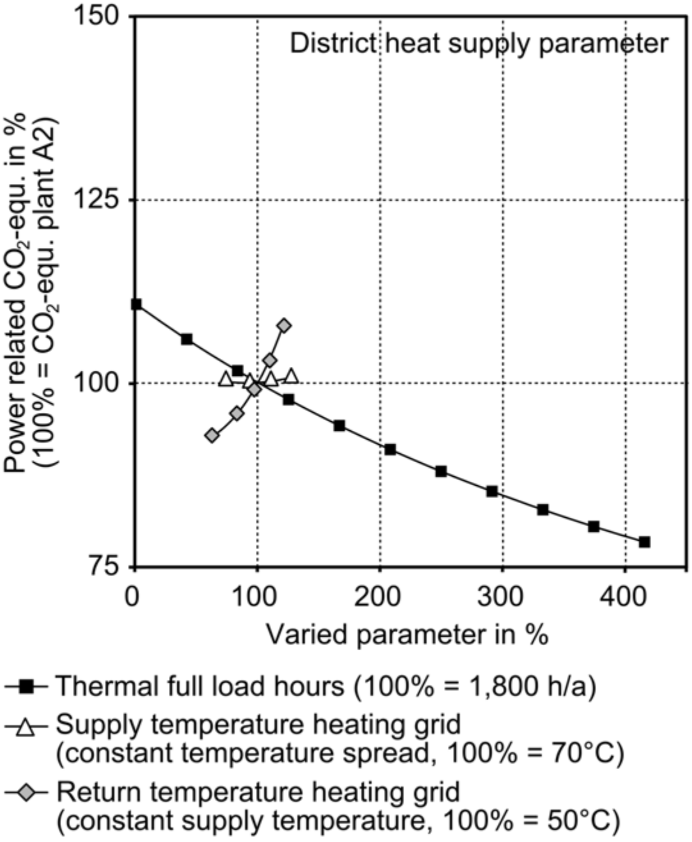
construction subsurface	91.8	91.1	93.8	94.4	94.1	95.6	95.7	95.3	96.9	97.1	97.0	97.8
construction surface	6.6	7.2	4.9	4.3	4.5	3.3	3.4	3.7	2.4	2.1	2.2	1.6
operation	1.5	1.6	1.2	1.2	1.3	1.0	0.8	0.9	0.6	0.7	0.7	0.5
decomissioning	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1

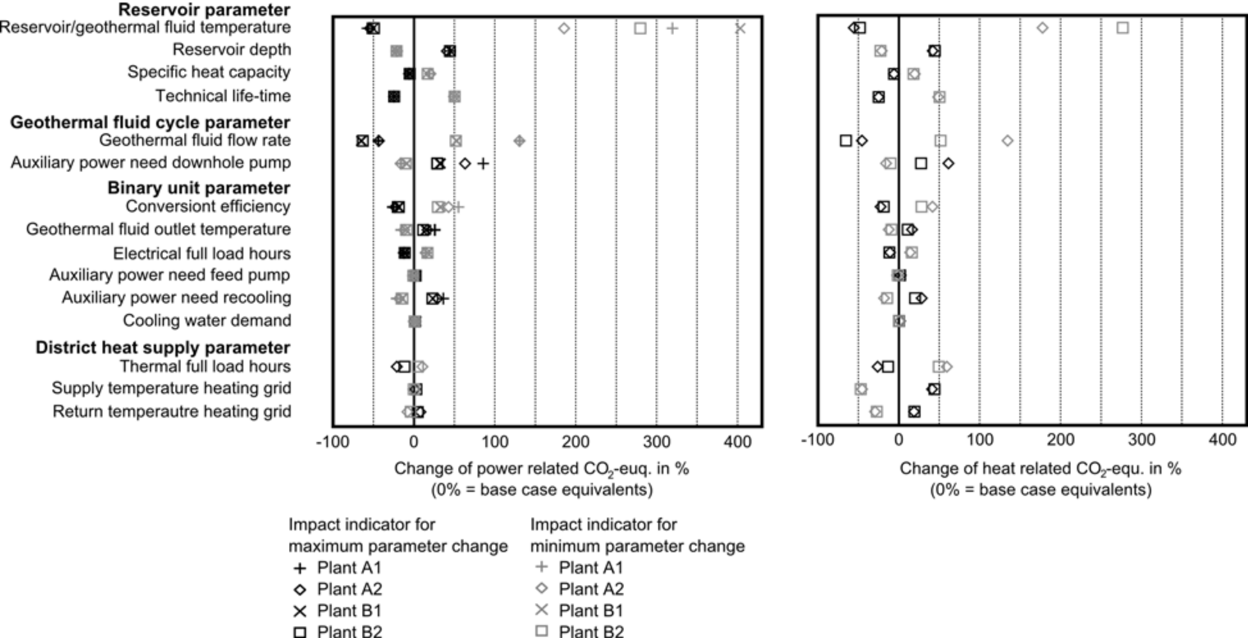

CO$_2$-equivalent
CED
SO$_2$-equivalent
PO$_4^{3-}$-equivalent
energy drilling
drilling mud
casing
cementation
reservoir enhancement
other
0
25
50
75
100
Break down of impact indicators in %
(construction subsurface, plant A1)

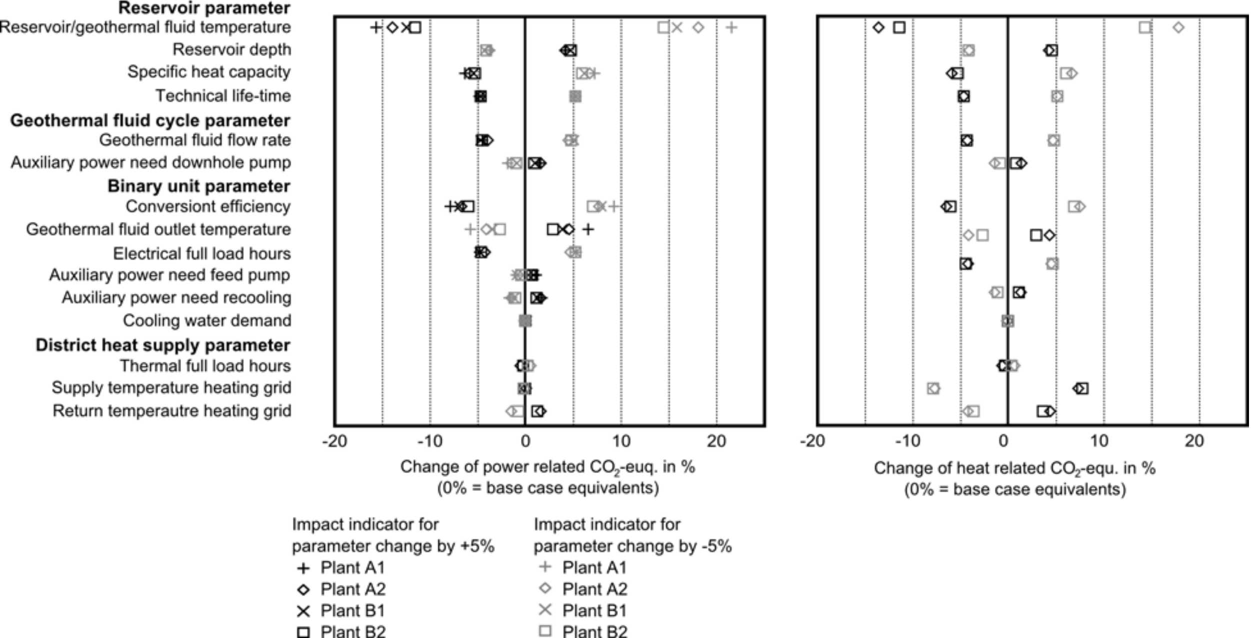

Reservoir parameter
Power related CO_2-equ. in % (100% = CO_2-equ. plant A2)
300
225
150
75
0
50
75
100
125
150
Varied parameter in %
Reservoir / geothermal fluid temperature (constant reservoir depth, 100% = 125°C)
Reservoir depth (constant reservoir / geothermal fluid temperature, 100% = 3.8 km)
Specific heat capacity (100% = 4 kJ/(kgK))
Technical lifetime (100% = 30 a)

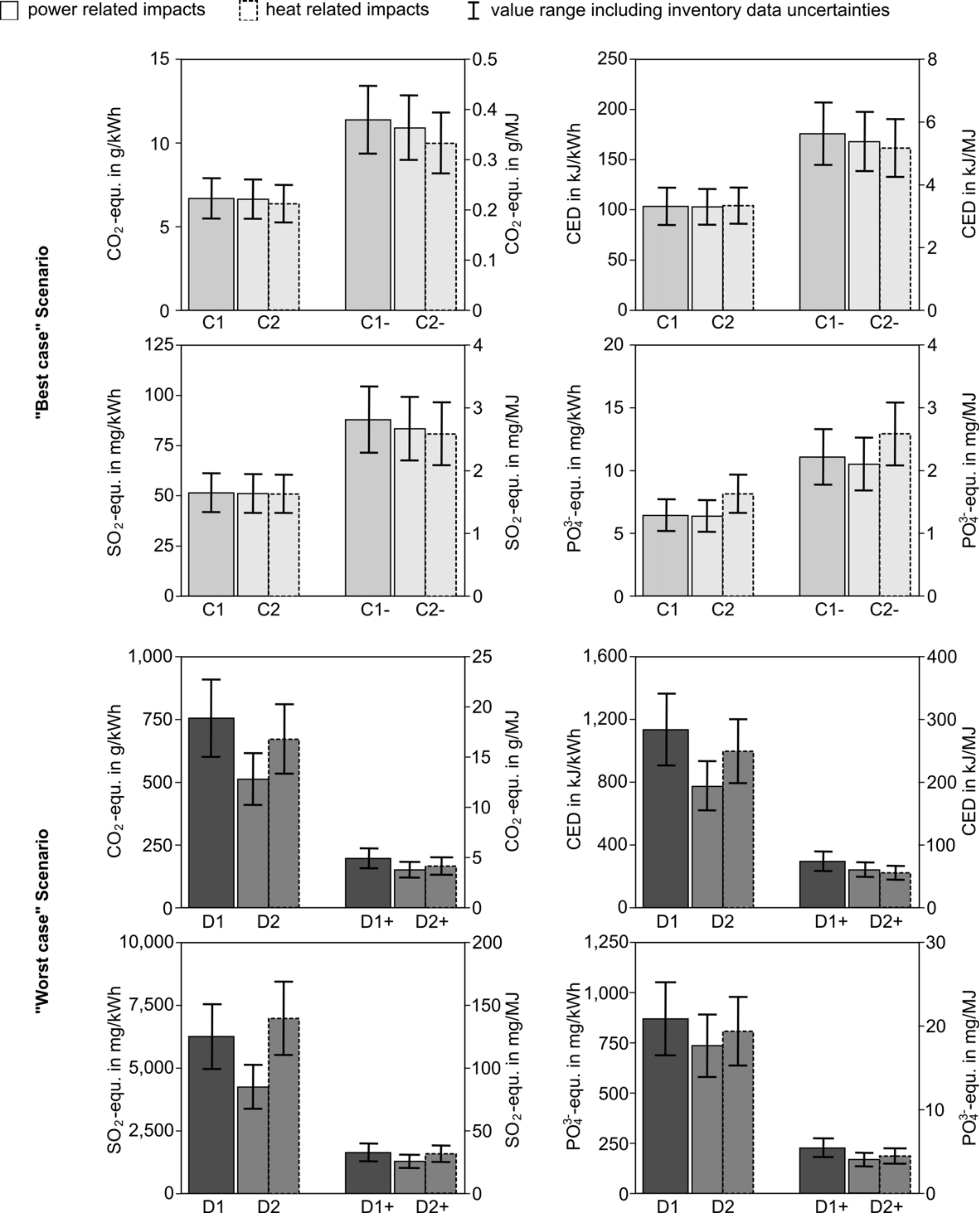

Geothermal fluid cycle parameter
Power related CO_2-equ. in % (100% = CO_2-equ. plant A2)
300
225
150
75
0
0
50
100
150
200
250
Varied parameter in %
Geothermal fluid flow rate (constant specific auxiliary power need of the downhole pump, 100% = 250 m^3/h)
Auxiliary power need donwhole pump (100% = 1.3 kW/(m^3/h))

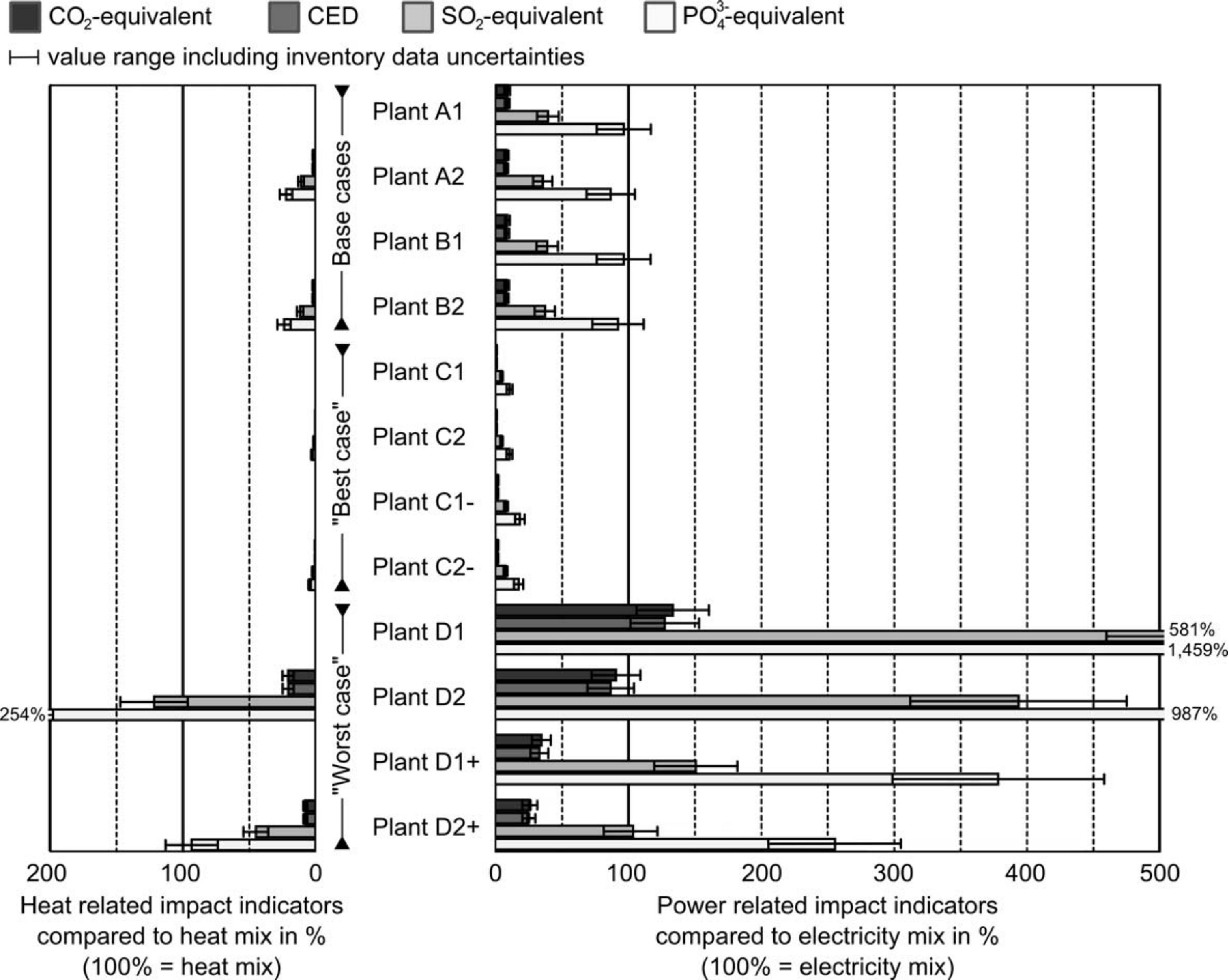

Binary cycle parameter
Power related CO_2-equ. in % (100% = CO_2-equ. plant A2)
150
125
100
75
0
50
100
150
200
Varied parameter in %
Conversion efficiency (100% = 9.7%)
Geothermal fluid outlet temperature (100% = 60°C)
Auxiliary power need feed pump (100% = 10%)
Auxiliary power need recooling (100% = 20 kW_{el} /MW_{th})
Cooling water demand(100% = 3 m^3/h/MW_{th})
Electrical full load hours (100% = 7,000 h/a)


District heat supply parameter
Power related CO_2-equ. in % (100% = CO_2-equ. plant A2)
150
125
100
75
0
100
200
300
400
Varied parameter in %
Thermal full load hours (100% = 1,800 h/a)
Supply temperature heating grid (constant temperature spread, 100% = 70°C)
Return temperature heating grid (constant supply temperature, 100% = 50°C)


Reservoir parameter
Reservoir/geothermal fluid temperature
Reservoir depth
Specific heat capacity
Technical life-time
Geothermal fluid cycle parameter
Geothermal fluid flow rate
Auxiliary power need downhole pump
Binary unit parameter
Conversient efficiency
Geothermal fluid outlet temperature
Electrical full load hours
Auxiliary power need feed pump
Auxiliary power need recooling
Cooling water demand
District heat supply parameter
Thermal full load hours
Supply temperature heating grid
Return temperautre heating grid
-100
0
100
200
300
400
Change of power related CO_2-euq. in %
(0% = base case equivalents)
-100
0
100
200
300
400
Change of heat related CO_2-equ. in %
(0% = base case equivalents)
Impact indicator for
maximum parameter change
+ Plant A1
◇ Plant A2
× Plant B1
□ Plant B2
Impact indicator for
minimum parameter change
+ Plant A1
◇ Plant A2
× Plant B1
□ Plant B2


Reservoir parameter
Reservoir/geothermal fluid temperature
Reservoir depth
Specific heat capacity
Technical life-time
Geothermal fluid cycle parameter
Geothermal fluid flow rate
Auxiliary power need downhole pump
Binary unit parameter
Conversiont efficiency
Geothermal fluid outlet temperature
Electrical full load hours
Auxiliary power need feed pump
Auxiliary power need recooling
Cooling water demand
District heat supply parameter
Thermal full load hours
Supply temperature heating grid
Return temperautre heating grid
-20
-10
0
10
20
Change of power related CO2-euq. in %
(0% = base case equivalents)
-20
-10
0
10
20
Change of heat related CO2-equ. in %
(0% = base case equivalents)
Impact indicator for parameter change by +5%
+ Plant A1
◇ Plant A2
× Plant B1
□ Plant B2
Impact indicator for parameter change by -5%
+ Plant A1
◇ Plant A2
× Plant B1
□ Plant B2


power related impacts
heat related impacts
value range including inventory data uncertainties
"Best case" Scenario
"Worst case" Scenario
CO$_2$-equ. in g/kWh
CO$_2$-equ. in g/MJ
CED in kJ/kWh
CED in kJ/MJ
SO$_2$-equ. in mg/kWh
SO$_2$-equ. in mg/MJ
PO$_4^{3-}$-equ. in mg/kWh
PO$_4^{3-}$-equ. in mg/MJ
C1
C2
C1-
C2-
D1
D2
D1+
D2+
0
5
10
15
0.1
0.2
0.3
0.4
0.5
50
100
150
200
250
2
4
6
8
25
75
125
1
3
20
1,000
750
500
250
25
400
800
1,200
1,600
300
400
10,000
7,500
5,000
2,500
150
1,250


CO2-equivalent
CED
SO2-equivalent
PO43--equivalent
value range including inventory data uncertainties
Base cases
"Best case"
"Worst case"
Plant A1
Plant A2
Plant B1
Plant B2
Plant C1
Plant C2
Plant C1-
Plant C2-
Plant D1
Plant D2
Plant D1+
Plant D2+
581%
1,459%
987%
254%
200
100
0
0
100
200
300
400
500
Heat related impact indicators compared to heat mix in % (100% = heat mix)
Power related impact indicators compared to electricity mix in % (100% = electricity mix)