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ENVIRONMENTAL EFFECTS OF HEAT PROVISION FROM GEOTHERMAL ENERGY IN COMPARISON TO OTHER SOURCES OF ENERGY

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ABSTRACT

Geothermal energy, as well as other renewable sources of energy, can be used instead of fossil fuel energy to meet the given heat demand in Europe and is claimed to contribute to the reduction of greenhouse gas emissions as well as other energy based environmental effects. However, the use of geothermal energy can also cause adverse effects on the environment. The goal of this paper is it to compare heat provision from geothermal energy with the provision of heat from other renewable energy and fossil fuel energy sources. This will be done based on Life Cycle Analysis (LCA) methodology for the potential impacts "finite energy resource consumption", "additional anthropogenic greenhouse effect", "acidification of lakes and rivers" and "human and eco-toxicity (based on SO_2 and NO_x)". In particular, a comparison of the heat provision from the soil and from groundwater with heat pumps, from hydrothermal resources and from deep wells as well as from biomass, from solar collectors and from light oil and natural gas is investigated. The investigation shows that the heat provision from geothermal energy could contribute considerably to reduce the environmental impact caused by the use of fossil fuel energy to accomplish the same supply task.

1. INTRODUCTION

The use of geothermal energy as well as other renewable sources of energy instead of using fossil fuels to meet the given heat demand in Europe is claimed to reduce greenhouse gas emissions as well as other energy based environmental effects. But, the use of geothermal energy is connected with some adverse effects on the environment.

Therefore from an environmental point of view the substitution of fossil fuel by geothermal energy or other renewable energy makes sense only if the environmental effects necessarily caused by the provision of useful energy could be reduced throughout the overall life cycle for the provision of useful energy. This is true because environmental effects caused by the provision of useful energy happen not only at the site of the conversion plant. The provision of the energy carrier and the production of the material a heat provision plant is made from can also have effects on the environment.

On this background the aim of this paper is it to analyse and compare selected environmental effects caused by the heat provision from geothermal energy and other renewable and fossil energy carrier. This is done throughout the whole life cycle based on the LCA methodology (i. e., "cradle" to "grave" approach) exemplarily for the circumstances given in Germany. This is done for the following environmental aspects:

- fossil energy carrier needed for the provision of useful energy (aspect "finite energy resource consumption"),
- airborne emissions with an impact on global climate (aspect "additional anthropogenic greenhouse effect"),
- airborne emissions with the ability to form acids (aspect "acidification of lakes and rivers"), and
- airborne emissions with an toxic impact on humans and the natural environment exemplarily for SO_2 and NO_x (aspect "human- and eco-toxicity").

There exist very different possibilities to provide heat from renewable energy and from fossil energy carrier. They show very different technical characteristics. Therefore within the following explanations three different typical supply cases are analysed (i. e., "Residence", "Small District Heating System", "Large District Heating System") to allow an easy comparison. In particular the following renewable and fossil fuel sources of energy for heat provision are analysed.

- geothermal energy from soil and groundwater with heat pumps for residences;
- geothermal energy from hydrothermal resources for large district heating systems;
- geothermal energy from deep wells for small district heating systems;
- biomass fired in boilers for residences as well as for small and large district heating systems,
- solar energy used in solar thermal collectors for residences and for small district heating systems and
- light oil and natural gas for residences as well as for small and large district heating systems.

To analyse these different options the methodological approach (i. e., LCA) is first described. Then the different supply tasks are presented in more detail. Based on the findings the results of the LCA are presented and discussed. Then some conclusions are drawn.

2. METHODOLOGICAL APPROACH

A Life Cycle Analysis (LCA) is defined by existing standards consisting of four steps. These different steps ("goal and scope definition", "inventory analysis", "impact assessment" and "interpretation") are briefly described below (cf. ISO 14040 (1997), prEN ISO 14041 (1997)). A differentiation is made between the general content of these steps within the LCA-methodology and the special adaptation within this investigation.

2.1 Goal and Scope Definition

General. In the step "goal and scope definition" the topic of the LCA has to be defined precisely. This includes the definition of the object (product, services, system or technique) to be assessed. This contains also the functional unit as well as a description of the system boundaries, the time reference, aims and criteria of the analysis and the assumptions. Also the environmental impacts to be investigated should be specified as well as the data considered within the balances of the energy and mass flows. For a comparison of different options the compared objects must use or be converted to the same functional unit.

Particular. For the LCA performed here the goal is a comparison of environmental effects (i. e., finite energy resource consumption, additional anthropogenic greenhouse effect, acidification of lakes and rivers, human- and eco-toxicity) of a heat production from various renewable energy as well as light oil and natural gas. The assessment object is the heat produced for three different supply tasks (i. e., "Residence", "Small District Heating System", "Large District Heating System") as defined in chapter 3. The functional unit is one GJ (Giga Joule; 10^9 J) of heat at plant gate with a statistical reliability of supply of 95 %.

2.2 Inventory Analysis

General. The second step, the "inventory analysis", contains the quantification of the energy and mass flows for the provision of the assessment object. These substances are balanced within this step from "cradle till grave". To realise this the process chain analysis could be applied.

The process chain analysis is a micro analysis. A complex system (like the production of heat from geothermal energy) is divided into well defined processes. Every process (e. g., combustion plant) is characterised by input (e. g., natural gas) and output flows (e. g., heat). Additionally to this a process shows also input flows from (e. g., air) and emissions to the environment (e. g., CO_2, NO_x). Since the input into one process results from other processes and the output of a process again is input to another process, a process chain can be assembled by linking the processes which describe the life cycle of a product (from "cradle" to "grave"). Although a process chain usually has a defined end (e. g., one GJ of heat), it is often difficult to define a clear beginning, as each process in the chain needs inputs delivered by other processes (exception: gain of ore). This means, that for practical reasons it is often necessary to end the chain by neglecting non consequential links after a certain number of steps.

Particular. Based on the process chain analysis the consumption of primary energy carrier as well as some emissions are balanced according to the parameters defined within section 2.3.

2.3 Impact Assessment

General. The third step of an LCA is "impact assessment" which includes the determination or quantification of the potential adverse effects that are caused by the input and output flows of the investigated system. Therefore the results from the "inventory analysis" are converted to potential environmental effects or totaled to provide environmental indicators.

Particular. For this investigation the following environmental effects are analysed in detail (cf. Heijungs et al (1992)).

- Finite Energy Resource Consumption. It is defined as the sum of the primary energy content of all non renewable energy carriers. This includes all processes necessary for utilisation, operation and demolition of a product. This value includes the primary energy content of fossil energy fuels like hard coal, lignite, crude oil and natural gas as well as other energy sources like uranium ore.
- Additional Anthropogenic Greenhouse Effect. This is an indicator of the change in the heat radiation absorption of the atmosphere. For different emissions with an effect on global climate, Global Warming Potentials (GWP) have been developed to assess the overall effect due to anthropogenic greenhouse gas emissions. Carbon dioxide (CO_2) is defined as the reference substance (CO_2; i. e., 1 kg CO_2-Eq./kg CO_2). Other greenhouse gases are methane (CH_4; i. e., 21 kg CO_2-Eq./kg CH_4) and nitrous oxide (N_2O; i. e., 310 kg CO_2-Eq./kg N_2O). The sum of these greenhouse gas emissions is stated in CO_2-equivalents (CO_2-Eq.).
- Acidification of Lakes and Rivers. This is an indicator of the potential ability of a substance to form an acid or to provide H^+-atoms. Sulphur dioxide is defined as the reference substance (SO_2; i. e., 1 kg SO_2-Eq./kg SO_2). Other emissions with an acidification effect are nitrogen oxide (NO_x; i. e., 0,7 kg SO_2-Eq./kg NO_x), ammonia (NH_3; i. e., 1,88 kg SO_2-Eq./kg NH_3), hydrochloric acid (HCl; i. e., 0,88 kg SO_2-Eq./kg HCl) as well as hydrogen fluoride (HF; i. e., 1,6 kg SO_2-Eq./kg HF). The sum of releases of these gases is stated in SO_2-equivalents (SO_2-Eq.).
- Human- and Eco-toxicity. A very broad variety of airborne emissions released from boilers are characterised by an impact on humans and the natural environment. Emissions of sulphur dioxide (SO_2) and nitrogen oxide (NO_x) are examples analysed here.

2.4 Interpretation

General. "Interpretation" is the phase of an LCA in which the findings from the inventory analysis and the impact assessment are combined together in order to reach conclusions and recommendations consistent with the goal and scope of the LCA. But there exists no general rule for executing the interpretation step. Due to the general problem of the many different ways of producing the example product heat, very different environmental impacts result and an overall objective judgement is hard to compile. This is the reason why in most cases only a discussion of the results of the impact assessment is realised.

Particular. In this paper an interpretation according to the rules underlying an LCA is not realised. But within the impact assessment the main results are discussed.

3. HEAT FROM RENEWABLE AND FOSSIL ENERGY

To allow a comparison of environmental aspects of different possibilities to provide heat, different supply tasks have to be defined. This is especially true because the different technologies to use renewable energy work for technical reasons at very different capacity ranges. Therefore three different supply tasks are defined.

- "Residence". In the lower capacity range the heat supply for a residence is assumed. The installed thermal capacity is 40 kW (Kilo Watt; 10^3 W). The full load hours are assumed to be at 1 800 h/yr (hours per year).
- "Small District Heating System". For the medium capacity range a small district heating system with an overall installed thermal capacity of 3,000 kW is defined to provide heat for a small suburb without any industrial customers. Therefore the full load hours are again defined with 1,800 h/yr. The heat losses within the distribution network is 15 %. Due to economic reasons the district heating system consists in most cases of a system for the base load (provided mostly by a system using renewable energy) and for the peak load (in most cases a boiler fired with natural gas or light oil).
- "Large District Heating System". To analyse the upper border of thermal capacities to be installed in heating systems based on renewable energy a large district

heating system with an overall installed capacity of 10,000 kW is assumed. To allow an easy comparison to the other systems also the heat supply for residences without industrial customers is assumed (i. e., 1,800 h/yr). Again the distribution losses are 15 %. Also such large systems consists of a system for the base load (a system mostly based on renewable energy) and for the peak load (mostly a boiler fired with oil or gas).

For these different supply tasks the following heat provision systems based on renewable and fossil energy could be applied (cf. Kaltschmitt et al (1999), Kaltschmitt and Wiese (1997), Kaltschmitt and Reinhardt (1997)).

Geothermal Energy from Soil and Groundwater. Due to the low temperature level of geothermal energy extracted from the soil and from the groundwater, a heat pump is needed that uses electricity from the grid. To extract the heat from the soil, horizontal laid earth collectors and vertical drilled wells are assumed. Groundwater is used via a production and injection well. Due to economic reasons such systems are only used for the provision of heat in homes (i. e. "Residences").

Geothermal Energy from Deep Wells. Geothermal energy from the deep underground can be extracted based on deep wells where a heat transfer medium is circulated. Due to the relatively low heat flow in the underground and in most cases – due to economic reasons – not very deep wells, a heat pump is needed to provide heat at a temperature level which is sufficient for meeting a given energy demand. Such systems for the provision of heat from geothermal energy with the help of a heat pump driven by electrical energy operate only for the provision of base load. Peak load are typically produced based on fossil fuel energy. The thermal capacities are typically in the range of a few MW (i. e. "Small District Heating System").

Geothermal Energy from Hydrothermal Resources. Under certain conditions, deep underground layers exist with a high porosity and permeability filled by warm or hot water. If such layers could be accessed by wells the water could be extracted and transported to the surface. Here the geothermal energy is removed from these geofluids using a heat exchanger to provide the energy for heating a district heating system. The geofluid cooled down in the heat exchanger is then injected back into the underground layer with an injection well. Depending on the temperature of the geofluid a heat pump could be needed to ensure a temperature level is provided to meet demand characteristics. Due to economic reasons such plants are only realised with thermal capacities of more than 5 MW (i. e. "Large District Heating System") with a base load system based on geothermal energy and a peak load system based on fossil fuel energy.

Solarthermal Energy. The radiation from the sun could be used in solar collectors to provide heat. Due to the poor correlation between the solar radiation and the overall heat demand in Europe, such systems provide in most cases only sanitary hot water. For covering the heat needed for heating the living space, solar collectors can only make a small contribution in the transitional period. Therefore some effort is required to develop seasonal storage facilities for heat. Solar collectors are in use in homes (i. e., "Residence") and together with a seasonal storage of heat from small district heating systems (i. e., "Small District Heating System"). In each case a backup system with the needed overall thermal capacity is needed to provide heat when the sun is not available. It is assumed that this backup system is fired with fossil fuel energy.

Biomass. Solid biofuels could be used in combustion plants to provide heat. With such systems a broad range of thermal capacities is available. But for economic reasons, combustion plants above a few 100 kW use a peak load system based on fossil fuel energy. Therefore the use of solid biofuels (i. e., residual wood) partly in combination with fossil fuel energy is assumed for all three supply tasks (i. e., "Residence", "Small District Heating System", "Large District Heating System").

Fossil Fuel Energy. The use of fossil fuel energy for the provision of heat is state of the art technology for a very broad range of thermal capacities. Therefore the use of light oil or natural gas is possible for all supply tasks investigated here (i. e., "Residence", "Small District Heating System", "Large District Heating System").

4. RESULTS

Based on the methodological approach described in Section 2 and the frame conditions and the available technologies defined in Section 3, a balanced comparison of environmental impacts could be calculated. The results of this investigation are shown in Table 1. The different results are discussed in more detail within the following paragraphs (cf. Kaltschmitt et al (1999), Kayser (1999), Lux and Kaltschmitt (1997)).

"Residence". A heat provision for the supply task "Residence" is possible based on solar energy, biomass, geothermal energy from soil and groundwater as well as from light oil and natural gas. The use of geothermal energy from hydrothermal resources and extracted with deep wells is not possible due to technical and economic reasons.

By comparing the environmental indicators analysed it is obvious that heat provision from fossil resources leads to the highest emissions. This allows the conclusion that the use of renewable energy allows a substantial reduction of energy based environmental effects – but to a different extent.

Comparing the different renewable energy options for heat provision shows that heat provision from solar energy and from geothermal energy extracted from soil and groundwater are characterised by environmental indicators that are in the same order of magnitude. This is due to very different reasons.

- Only heat provision by solar energy is emission free – the substances emitted during the production of the solar collectors are almost negligible referring to the heat provided during the technical life time of the solar collector. The emissions shown in Table 1 therefore results mainly from the heat provision of the backup system. It runs with fossil energy and is needed to guarantee a heat supply for the defined supply task also when no solar energy is available (i. e., in winter time). The same applies also in principle for the finite energy resource consumption.
- To provide useful heat from geothermal energy from soil and groundwater requires a heat pump. Such a system component in the thermal capacity range needed for this supply task runs with electrical energy in most cases. Therefore the emissions released into the atmosphere during the production of the electricity needed by the heat pump are attributed to the heat provision. This results in the fact that the emissions shown in Table 1

result primarily from the energy provided from a power plant system (here the power plant system from Germany). Again the emissions released during the production (and demolition) of the heating system based on geothermal energy are low compared to the overall substances released during the operation of such a system. Accordingly, the emissions shown in Table 1 are strongly dependent on the system which provides the electrical energy. A power plant system based fully on hydropower would result in very low emissions and one based exclusively on coal fired power plants with a low efficiency rate in comparatively high emissions. Therefore the environmental advantage and disadvantage of heat provision from geothermal energy from soil and groundwater via heat pumps depends mainly on the environmental effects of the electricity provision system needed to provide the energy for running the heat pump. This is also true for the finite energy resource consumption in a figurative sense.

Compared to the environmental effects of heat from solar and geothermal energy, heat provision from biomass shows different characteristics.

- The consumption of finite energy resources is quite low. For the provision of solid biofuels to the combustion plant (i. e., Diesel fuel for transportation) and the operation of the plant itself (i. e., electricity from the grid) only very little fossil fuel energy is needed. Also biomass is already stored solar energy. Therefore this system needs no backup system. This sums up to the very low figure for the finite energy resource consumption shown in Table 1.
- The low emissions of CO_2-Equivalents result mainly from CO_2 released during the provision of the biomass because fossil fuel energy is needed to make the biofuels available at the combustion plant. But the CO_2-emissions released during the combustion of the biomass does not contribute to the additional anthropogenic greenhouse effect because this CO_2 has been removed from the atmosphere during the growth of the plant (i. e., closed carbon cycle).
- The releases of SO_2 and NO_x as well as the SO_2-Equivalents are dominated by the emissions from the combustion of the biomass in the boiler. The release of these gases in the prechains is small. Due to the low sulphur content of the biomass the SO_2-emissions are fairly low. Due the combustion technology used in small scale plants which show still a certain improvement potential the NO_x-emissions are relatively high. They are also responsible for the relatively high releases of SO_2-Equivalents.

But compared to the environmental effects of the use of fossil energy for fulfilling the same supply task, the use of renewable energy is much more promising from an environmental point of view. For that purpose the use of geothermal energy from soil and groundwater is a very promising possibility – if the electricity needed for operating the heat pump is produced with a low environmental impact.

"Small District Heating System". Heat for the supply task "Small District Heating System" can be provided with solar energy based systems, with biomass fired boilers, with geothermal energy extracted with deep wells as well as from systems bases only on light oil or natural gas. Geothermal energy from soil and groundwater as well as from hydrothermal resources is, due to economic (and technical) reasons, not an option for the thermal capacities needed for this supply task.

A comparison of the environmental effects investigated here of the different systems shows a very inhomogeneous picture. This is true due the following reasons.

- The environmental indicator figures for the heat provision from solar energy are relatively high compared to the other systems based on renewable energy. This is true because solar energy can only contribute to a small part of the overall heat demand due to the poor correlation of the solar energy supply and the heat demand. Even if a system is assumed with a seasonal storage facility, backup systems are needed necessarily which are assumed to be fired by fossil fuels. Also the environmental effects shown in Table 1 are mainly defined by the operation of the plant; the production and demolition contribute only little to the LCA results. Therefore the environmental key figures for the solar thermal system are only slightly lower than the heat provision for the same supply task based exclusively on fossil energy.
- For the biomass-fired system the same is true as discussed already for the "Residence" system. But in the capacity range of "Small District Heating System" due to economic reasons the biomass boiler is only used for the base load and the peak load is provided by the use of fossil energy. Therefore the environmental indicator figures are higher compared to the values shown for the biomass boiler for the "Residence" where no peak load provision based on fossil energy is assumed (cf. Table 1).
- Heat provision from deep wells is due to technical reasons only possible with heat pumps. Additionally the geothermal system provides base load and the peak load is provided by the use of fossil energy. Therefore the emissions are in the same order of magnitude as the system based on geothermal energy from soil and groundwater ("Residence"). They also depend very strongly on the electricity provision system if an electrically driven heat pump is used.

Compared to the systems based on renewable energy the results of the LCA (i. e., the indicator figures for the environmental impacts analysed here) are higher for fossil fuel energy. Therefore the conclusion can be drawn that the use of renewable energy can substantially contribute to reducing energy-based environmental effects. This is also true for the use of geothermal energy extracted from deep wells.

"Large District Heating System". The supply task "Large District Heating System" can be met with biomass fired boilers, with geothermal energy from hydrothermal resources and from systems bases exclusively on fossil energy. Geothermal energy from soil and groundwater as well as from deep wells is not applicable in this thermal capacity range due to economic (and technical) reasons.

The results again show a non-uniform picture. This is mainly due to the relations and frame conditions discussed so far.

- The biomass based system consists of a base load system operating on biomass and a peak load system fired with fossil energy. This explains the higher emissions level compared to the system based on biomass only assumed for the supply task "Residence". The other effects (i. e., relatively low emissions of CO_2-Equivalents and SO_2, relatively high emissions of NO_x and SO_2-Equivalents) are discussed already (see above).
- The use of hydrothermal resources provides the base load only. Depending on the conditions in the reservoir

additionally a heat pump could be needed. The peak load is – in most cases – to a different extent provided by systems based on fossil energy. Therefore the lower bound of the environmental indicator figures shown in Table 1 refer to a system with very good characteristics (i. e., high temperatures above 90 °C) where only very little fossil energy is needed (i. e., low environmental indicator figures as a result of the LCA balances because these figures are determined by the operation of the plant; the construction and demolition of the plant influences these figures only to a very limited extend). As a consequence of these conditions the environmental indicator figures increase when the characteristics of the hydrothermal resource decrease (i. e., lower bound in Table 1).

- The use of fossil fuel energy to cover the energy demand defined within the "Large District Heating System" shows the highest environmental indicator figures. As for the other supply tasks the lower bound is based on systems based on natural gas and the upper bound on light oil. Because the use of natural gas is more efficient, the fuel characteristics are more promising, and the combustion technology is more advanced, a heat provision from natural gas shows much lower emissions compared to light oil.

In conclusion the use of renewable energy can contribute to reducing the environmental effects associated with the use of fossil fuel energy for the provision of heat.

5. FINAL CONSIDERATIONS

The goal of this paper is to provide a comparative analysis of the environmental effects caused by the provision of heat from renewable and fossil energy. To quantify some important environmental effects the LCA methodology has been applied.

By comparing the environmental effects analysed within this paper the following statements can be made.

- The use of renewables could contribute to an environmentally more friendly heat supply system. This is true for all renewable energy possibilities investigated here (i. e., geothermal energy from soil and groundwater, geothermal energy extracted from deep wells, geothermal energy from hydrothermal resources, solar energy and biomass).
- Due the low energy density of some renewable sources of energy and the varying energy supply availability (like solar energy) backup systems are needed to meet a defined supply task. Such backup systems are based mainly on the use of fossil fuel energy. Additionally especially for systems with thermal capacities in the MW range, only the base load can be provided by renewable sources of energy due to economic reasons. Therefore the environmental profitability of such renewable fossil mix systems are in most cases defined by the share of the overall heat provided from fossil energy. This is also true because the environmental effects caused by systems for the provision of heat are mainly defined by the operation of the system. Construction and demolition influences the results of the LCA balances to only a very limited extent.
- Compared to other renewable sources of energy the use of geothermal energy is a promising option from an environmental point of view. The environmental advantage depends on the share of fossil fuel energy which is still needed to provide useful energy for a defined supply task (i. e., environmental effects of the electricity needed to power the heat pumps or the share of peak load provided by fossil fuel energy in larger plants). But geothermal energy with promising characteristics could make a substantial contribution to a more environmentally friendly energy supply system.

In conclusion, the use of geothermal energy could contribute to a much more environmentally benign energy supply in Europe. Depending on its share in the total supply of energy, geothermal energy could help save fossil fuel sources of energy and avoid the environmental effects associated with fossil fuel combustion. This means that geothermal heating stations could also contribute significantly to the abatement of CO_2 emissions that the European Union has undertaken to achieve. Additionally the use of geothermal energy is characterised by a good security of supply, enjoys a reasonable degree of public acceptance, and, owing to the experience gained on demonstration plants, is already available at a high level of operating safety.

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Table 1 Comparison of different environmental key figures for the heat provision from renewables and from fossil energy

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

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