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Life Cycle Assessment and Scenario Analyses of an operating geothermal Heat Project in the Southern German Molasse Basin

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Abstract:

In order to mitigate climate change, the expansion of renewable sources especially in the fossil-dominated heating sector is necessary. Geothermal sources represent a promising low-carbon alternative for heat supply. In this study, a Life Cycle Assessment of an operating deep geothermal heat plant in the Southern German Molasse Basin is conducted according to ISO 14040 and 14044. The plant utilizes a hydro-geothermal source and consists of a total of two production wells and one injection well with thermal water temperatures of up to 107 °C and an output of 16.7 MW. For peak load and redundancy, three oil boilers with a total capacity of 17 MW are installed. The heat plant is connected to a 48.5 km district heating network for the supply of 1800 customers. As functional unit 1 kWh net heat at the customer is chosen. For the impact categories Global Warming Potential (GWP), fossil resource scarcity and terrestrial ecotoxicity are considered. The environmental impact amounts to 78.5 g CO_2-eq./kWh, 29.2 g oil-eq./kWh and 399.0 g 1,4-DCB/kWh, respectively. In addition to the main results, selected scenarios have been analyzed with regard to the potential of switching the electricity mix and the peak load coverage between oil, natural gas and biomethane. The results show that switching to a renewable electricity mix leads to the biggest reduction with 57.8 % for the GWP.

Keywords:

Geothermal heat plant, district heating, Life Cycle Assessment; peak load coverage, electricity mix, Sustainability

1. Introduction

In order to meet the objective of the IPCC and limit the anthropogenic impact on the environment, it is essential to decarbonize the heating sector. In Germany, especially, the share of renewable sources for heat is considerably low with only 16.5 % [1]. Geothermal energy has great potential and could substitute up to 40 % (7 655 MW) of the heat demand in the state of Bavaria [2]. Therefore, the technology has gained political interest also due to the independence of fossil fuel supply.

However, even with this technology, which is characterized by the costly deep drilling, the question of how well it is compatible with the climate is open. The Technical Expert Group on Sustainable Finance has set a threshold of 100 g CO_2-eq./kWh that makes a technology compatible with the Paris climate agreement [3]. Additionally, this threshold decreases every 5 years until net zero in 2050. This ensures the necessity to identify strategies for the reduction of Global warming potential (GWP).

In this study, a LCA is conducted analyzing the categories GWP, fossil resource scarcity (FRS) and terrestrial ecotoxicity (TE) for a currently operating geothermal heat plant in the Southern German Molasse Basin in the greater Munich area. Additionally, the influence of auxiliary energy is investigated and the potential of reducing the environmental impact is analyzed through scenario analyses regarding electricity mix and peak load coverage.

2. Goal and Scope

The LCA in this study is conducted according to ISO 14044 and 14040 [4,5] which include the four phases: definition of goal and scope, inventory analysis, impact assessment and interpretation. These phases are explained in detail in the next sections.

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2.1. Objective

The objective of this study is to conduct an LCA of a currently operating geothermal heat plant and its district heating network (DHN) in the Southern German Molasse Basin which includes the impact categories GWP; FRS and TE. Furthermore, the use of auxiliary energy is analyzed by conducting scenarios regarding the electricity mix and the peak load coverage. For the applied electricity mix the location based German electricity mix is compared to two renewable mixes (see Table 6). With the peak load coverage, the fuels light fuel oil, natural gas and biomethane are weighted up.

For the LCA, all energy and material flows for the life cycle stages construction, operation and decommission are considered. Thus, a cradle to grave approach is applied. To ensure comparability with other LCAs, a lifetime of 30 years is chosen, as is suggested by [6]. According to [7] and [8] DHNs exceed the life time of the heat plant with respectively minimally 40 and 50 a. Therefore, it is assumed that the DHN either will be used for another heat plant right away or remains unchanged in the ground until a new use. Either way there is no decommissioning scenario attributed to the life-cycle of the geothermal plant.

For operators of geothermal heat plants and decision makers the results can be of interest for developing strategies for the reduction of the environmental footprint along with planning future plants.

2.2. Functional unit

In order to present the result in a comparable way, all energy and material flows are related to one variable according to [4]. In this study, 1 kWh of net energy at the consumer has been selected for this purpose. This means that both DHN losses and the generation of auxiliary energy for peak load coverage and redundancy by oil boilers were considered.

2.3. Geothermal heat plant

In this section, the analyzed geothermal heat plant is presented. It is located in the Southern German Molasse Basin which is characterized by a porous water-bearing carbonate rock layer at a depth of 2000 to 3000 m in the greater Munich area, sloping down to the south [2]. Therefore, the plant relies on hydrothermal energy. It went into operation in 2005. The 104 °C hot water is drawn from two production wells and after the heat transfer at the heat exchangers it is fed back into one injection well. The heat exchangers are connected to the district heating network (DHN) as well as light fuel oil fuelled boilers which cover peak load and redundancy in case of maintenance or component failure. Through the DHN the heat plant supplies heat to 1800 customers. Relevant parameters can be found in Table 1.

Table 1. General Parameters of the geothermal heat plant [9]

Parameter	Value
Maximal geothermal energy	16.7 MW
Maximal energy by peak load and redundancy boilers	17 MW
Average operating hours full load	4234 h
Proportion of heat from geothermal energy	95 %
Proportion of heat from peak load and redundancy boilers	5 %
Production well 1 measured depth	4666 m
Production well 2 measured depth	4120 m
Injection well measured depth	3984 m
DHN	
DHN total length	48.5 km
DHN users	1800
Total installed load (2021)	29.75 MW

2.4. Data source and methodology

In this section, the important matter of data quality is addressed which needs to be included in any report for a LCA according to [4]. As far as possible for this study, primary data provided by the plant operator was used. If no data was available suitable literature was utilized. Thereby, it was ensured that the applicability was granted, e.g. through suitable geographical and time related similarity.

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To conduct the LCA, the software SimaPro (version 9.4.0.1) and the database ecoinvent (version 3.8) were utilized. Within ecoinvent, the system model “allocation cut-off by classification” was selected. This database provides an extensive selection of processes including pre-chain emissions in addition to direct emissions. ecoinvent provides the characterization factors to allocate environmental effects to conduct the life-cycle impact assessment (LCIA), which considers for example for the impact category GWP how much greenhouse gas is emitted for every energy and material in- and output collected in the LCI-phase. For the results the method ReCiPe midpoint (hierarchist) [10] is applied. Thereby, as impact categories, GWP (with a time horizon of 100 years, according to the hierarchist view) TE and FRS are selected.

3. Results and Discussion

3.1. Base Case

For the base case, the construction of the subsurface with the boreholes and the surface components are included. This involves the heat exchangers and peak load and redundancy boilers and plant parts. Additionally, the DHN is considered. The extensive LCI can be found in [9], any changes to the original LCI can be found in Table 7 in the appendix.

In Figure 1 the results for the base case are shown. Hereby, the general results are 78.6 g CO_2 eq./kWh for GWP, 399.0 g 1,4-DCB/kWh for TE and 29.3 g oil eq./kWh. It is apparent, that the operation phase dominates the environmental impact for all categories whereas for FRS the construction of the DHN also has a significant impact with 27 %. This is due to the light fuel oil product bitumen that is used for the asphalt which needs to be replaced for the installation of the pipes under streets (see also [9]).

Taking a closer look at the operation phase it is apparent that the main impact comes from the electricity consumption and the peak load and redundancy coverage. The latter has a high impact since it is oil based. The electricity consumption’s high impact is due to the high share of fossil sources like coal and natural gas in the German electricity mix. For the lifetime from 2005 to 2035 this amounts to 55.8 % (electricity mix based on [6] and [11]).The greatest influence of the operation is seen for the GWP: hereby the electricity consumption of the pumps leads to 62.0 % and the peak load and redundancy coverage to 21.2 %. For the TE the peak load coverage and redundancy have the biggest impact with 48.0 % and for FRS the electricity consumption dominates the impact with 43.1 %.

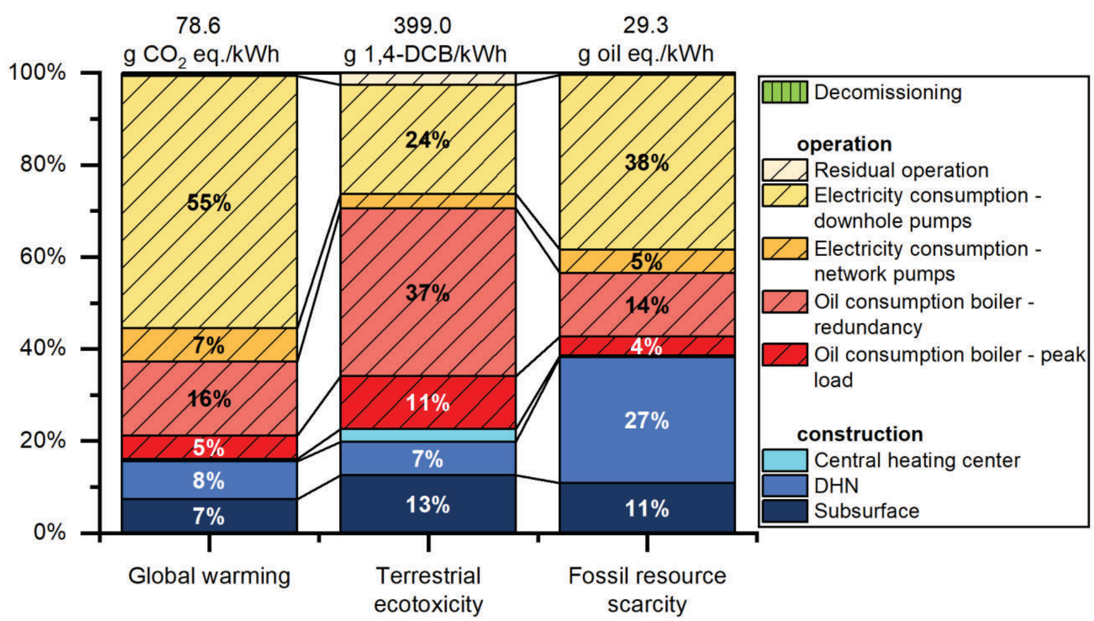

Figure 1. LCA results of a geothermal heat plant with DHN for the operating years of 2005-2035.

With these general results for GWP the threshold of 100 g CO_2/kWh proposed by [3] can be met with ease. They also propose an annual decrease in emissions until net zero 2050. Therefore, strategies should nevertheless be developed to further reduce the environmental impact. Since the single biggest contributors prove to be within the auxiliary energy namely electricity consumption as well as peak load and redundancy coverage, the impact of these is further examined by the following scenario analyses in the sections 3.2 and 3.3.

3.2. Peak Load Scenarios

Within this section, various technologies for managing peak energy demand are compared, with particular emphasis on those utilizing fuel-based solutions. The comparison is centered around the base case of oil-fuelled boilers for peak energy coverage, contrasted against the conventionally used natural gas alternative. Additionally, consideration is given to the renewable fuel source of Biomethane, which is derived by upgrading biogas through chemical means, increasing its methane content to match that of natural gas [12].

For the use of biomethane two scenarios are created, one with the sole use of biomethane as fuel and the second with a mixture of biomethane and natural gas. The latter is created as a realistic approach since the production volume of biomethane in Germany is limited which is due to being based on agricultural and animal waste as well as energy plants. The latter are in competition for cultivable land for food or feed crops as well as the use of biogas for electricity production (7.8 % of the electricity mix in 2022 [13]) [12,14]. The 10 % value is based on biomethane shares that are already currently commercially offered in the state of Baden-Württemberg in Germany [15]. Furthermore, it also fits within the range (8-12%) Arnold et al. [16] propose as realistic share of biomethane in the German gas grid by 2030. The following Table gives an overview over the different scenarios that are analysed.

Table 2. Peak load scenarios

Scenario	Base Case	Natural gas	Biomethane	90NG 10BM
fuel	Light fuel oil	Natural gas	Biomethane	90% natural gas and 10% Biomethane

For the LCI plant parts necessary for using light fuel oil, like the oil storage and catch basin are no longer needed and are therefore excluded. Through the ecoinvent data the gas production and the natural gas grid is considered proportionally. The material and energy input for the boilers are assumed to be the same for the fuel oil and gas, analogous to [17]. Since biomethane is used to substitute natural gas, the same infrastructure as for natural gas (gas network and boilers) is assumed as well as the same emissions for the burning in the boilers. The greenhouse gas emissions for the burning of biomethane, however, are considered as biogenic and are therefore not part of the GWP. The extensive LCI with the selected ecoinvent data for the components and the process of burning of the fuels can be found in the appendix in Table 8. An overview of the relevant parameters and considered infrastructure for the respective scenarios is shown in Table 3. For the scenario with 10 % biomethane and 90 % natural gas the models for natural gas and biomethane from Table 3 are considered proportionally.

Table 3. Parameters for the peak load scenarios with the base case (light fuel oil), natural gas and biomethane

Parameter	Base case	Natural gas	Biomethane
Degree of utilization	91 %[a]	96 %[b]	96 %[c]
Plant components	Boiler	Boiler[d]	Boiler[d]
	chimney	chimney	chimney
Fuel supply	Oil storage and catch basin	Natural gas network	Natural gas network
Direct emissions per kg light fuel oil/m^3 high pressure gas according to ecoinvent process	heat production, light fuel oil, at industrial furnace 1MW	heat production, natural gas, at boiler modulating >100kW	heat production, natural gas, at boiler modulating >100kW[e]

a: degree of utilization for the year 2019, assumed to remain the same over the life time
b: for a modulating, not condensing boiler according to [18]
c: Same value assumed as for natural gas
d: the same inputs are considered as for the oil fuelled boiler analogous to [17]
e: all emitted greenhouse gases are biogenic and are therefore not relevant for the GWP

In Figure 2 the LCA results for the peak load coverage are shown considering the different scenarios. Hereby, only the results for heat generation by the peak load boilers are shown as opposed to the heat generation of the whole geothermal plant.

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The results are depicted relative to the oil fuelled base case (BC). The other scenarios are the coverage by natural gas (NG), biomethane (BM) and the realistic scenario with 90 % supply by natural gas and 10 % biomethane (90NG10BM).

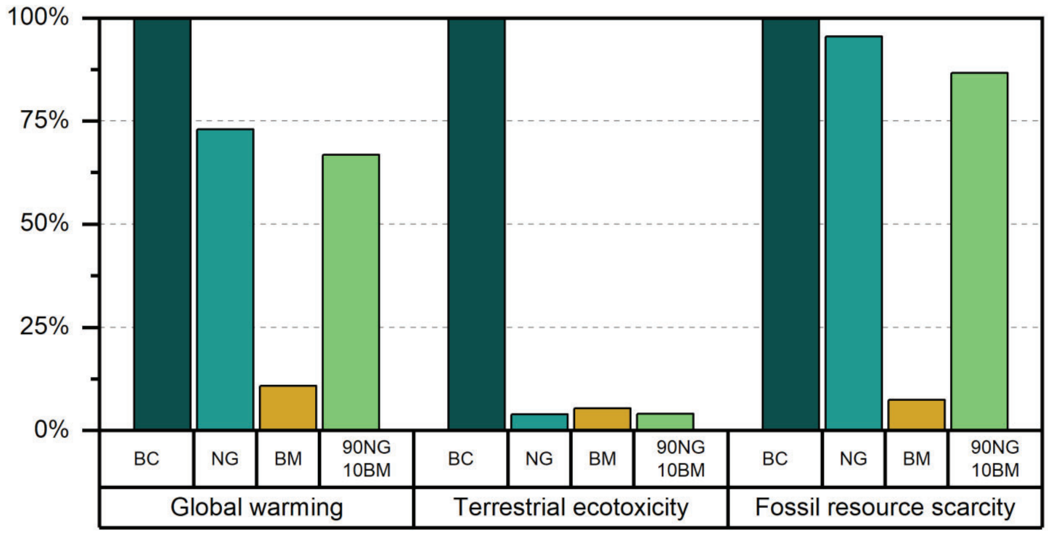

Figure 2. LCA Results of heat generation of different peak load coverage technologies: base case with light fuel oil (BC), natural (NG) and biomethane (BM) as well as a realistic mixture of 90 % natural gas and 10 % biomethane (90NG10BM) relative to the biggest contributor.

The relative results from Figure 2 are also shown in Table 4 as absolute values per kWh generated heat at the plant. In general, all gaseous fuels lead to a reduction of the environmental impact. Beside the higher emissions from burning oil compared to natural gas, this can be partly explained by the difference in utilization factors (that are generally higher for gas boilers than for using oil [19]). Additional contributions are the reduced fossil sources and emissions for biomethane compared to light fuel oil as well as reduced plant components. As expected, the biggest reductions for FRS and GWP are achieved by using biomethane. With the realistic scenario the GWP can be reduced by 33.3 % and the RRS by 13.4 %. For the TE the switch to the gaseous fuel in general leads to the biggest reduction since the oil combustion has a very high TE comparably.

Table 4. Results of the environmental impacts GWP, RE and FRS of the peak load coverage scenarios per kWh produced heat at the boilers (i.e. without DHN heat losses) considering construction, operation and decommissioning of the peak load components

	Base case	**Natural gas**	**Biomethane**	**90ng 10bm**
GWP [g CO_2/kWh]	353.5	257.9	38.2	235.9
TE [g 1,4-DCB]	4497.6	173.0	239.3	179.6
FRS [g oil eq]	110.9	105.8	8.2	96.1

If now the whole heat plant is considered again (see Table 5), with using 100% biomethane a reduction in GWP of 20.4 % can be achieved compared to the base case. Whereas the use of natural gas only reduces the total GWP by 3.2 %. Increasing the amount of biomethane in the gas network would lead to a significant reduction in GWP whereas for TE the switch to either gas greatly decreases the impact (49.4 % for natural gas) with natural gas having a slightly higher reduction potential than pure biomethane. The great effect on the heat plant concerning FRS can be again achieved with biomethane with a reduction of 17.6 %. Since FRS is based on the caloric value of the fossil fuels, the difference between oil and natural gas is mainly due to the higher degree of utilization assumed for the use of natural gas (see Table 3).

Table 5. Results of the environmental impacts GWP, RE and FRS of the peak load coverage scenarios per kWh produced heat by the whole geothermal plant

	Base case	Natural gas	Biomethane	90ng 10bm
GWP [g CO_2/kWh]	78.6	74.1	62.2	73.0
TE [g 1,4-DCB]	399.0	201.8	202.9	201.9
FRS [g oil eq]	29.3	29.1	24.2	28.6

To conclude, switching to natural gas has a small positive impact for GWP and FRS and a significant reduction for TE. Except for TE an increase of biomethane in the gas pipelines significantly decreases the environmental footprint of the plant. Although it has to be considered that the biomethane share in the gas network is dependent on the development of the gas market.

3.3. Renewable Electricity Mix Scenarios

To analyse the ecological potential of changing the consumed electricity mix, the base case is compared to two scenarios with renewable electricity mixes. The base case includes the location-based electricity mix in Germany for the respective electricity demands for each year over the plant's life time of 2005-2035. Whereas the future German electricity mix is obtained from the projection of [20]. To show the difference to a fully renewable mix, the base case is compared to the scenario with the mix of renewable energy of the year 2022 (RE22) [13]. Additionally, as an example of a commercial mix, a scenario containing 90 % hydro and 10 % wind power is created. The average shares of power sources can be found in Table 6.

Table 6. Composition of the examined electricity mixes with the base case displaying the general German electricity mix for the years 2005-2035 considering the differing yearly energy demands of the heat plant over the life time. Future mixes are modelled according to [20]. 90H10W displays an example of the potential of commercially available composition. RE22 is the market of renewable electricity in 2022 according to the German Federal Network Agency [13].

	Share [%]		
Energy source	**Base case**	**90H10W**	**RE22**
Fossil sources	55.8	0	0
Biomass	8.4	0	17.0
Hydro	3.6	90.0	5.3
Wind offshore	6.4	0	10.7
Wind onshore	17.4	10.0	43.3
Solar	7.8	0	23.8
Other renewables	0.6	0	0

In Figure 3 the environmental impacts in regard to GWP, TE and FRS are shown. The results are depicted as normalised to the base case with it being 100 %. With the renewable scenarios a big reduction can be achieved for the GWP with 50.6 % for EE22 and an even bigger reduction for 90H10W with 57.8 %. For FRS there is also a substantial reduction of 40.6 % for EE22 and 42.7 % for 90H10W. The TE is not influenced in the same way. There is only a reduction of 10.8 % for 90H10W and RE22 even exceeds the base case by 13.5 %. This can be explained by looking at the TE of the considered renewable technologies: Solar power has a TE of 3207 g 1.4-DCB/kWh, which is much higher than the other technologies which are located at most in the three-digit range. With this data it is clear that it cannot simply be assumed that environmental compatibility will always be improved by switching to renewable energy sources. Therefore, the technologies must be carefully selected.

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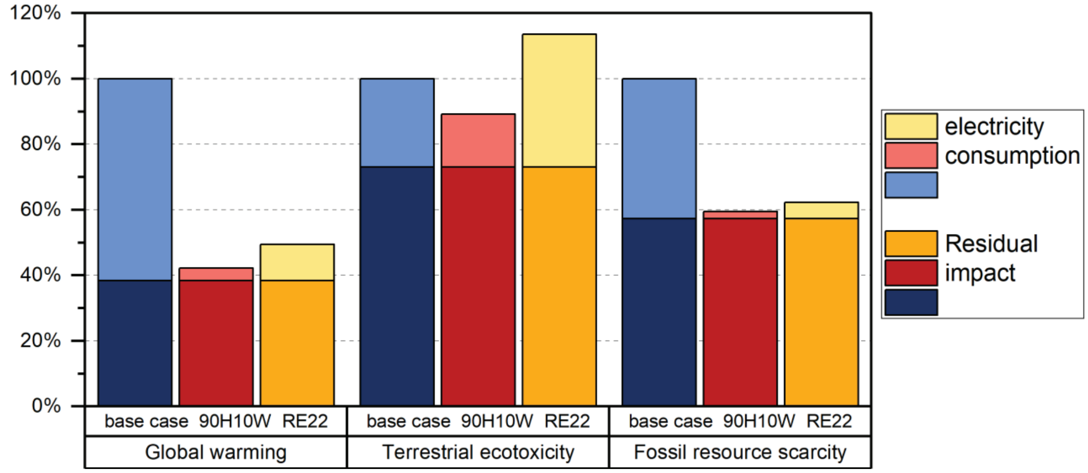

Figure 3. LCA results for the categories GWP TE and FRS for the Variation of the consumed electricity mix; comparison of the German electricity mix and the renewable mix for 2022 RE22 as well as a mix with 90 % hydro power and 10% wind.

The results reveal the potential of choosing an electricity contract with renewable energy. Even though there has to be close look at the composition of the renewable energy mix to ensure a substantial reduction for a holistic environmental improvement.

4. Conclusion

In this study a LCA for a currently operating heat plant in the Southern German Molasse Basin was conducted. Thereby the impact categories GWP, TE and FRS were chosen as well as the method ReCiPe Midpoint (H) [10]. All environmental impacts are related to the functional unit of 1 kWh net thermal energy. The environmental impact of the heat plant amounts to 78.5 g CO_2-eq./kWh, 29.2 g oil-eq./kWh and 399.0 g 1,4-DCB/kWh. The biggest contributor for all categories is the use of auxiliary energy with electricity consumption and peak load coverage by oil boilers. For FRS the DHN also has a significant share with 27.3 %. Therefore, the electricity mix and peak load coverage are analyzed with scenario analyses.

In the base case the electricity is modelled according to the electricity mixes for every year and the demand over the plant's life time. The future mix is modelled according to [20]. For a renewable energy mix the German mix of renewables of 2022 is applied as well as a mix of 90% hydro and 10 % wind power. The biggest reduction is achieved with the scenario 90H10W with 57.8 % for GWP, 10.8 % for TE and 40.5 % for FRS. Surprisingly, the RE22 scenario leads to a TE that is even bigger than the base case due to the high impact of solar power on that category.

For the peak load coverage, the base case with oil fueled boilers is compared to the fuels natural gas, biomethane and a realistic mixture of both with 90 % natural gas and 10 % Biomethane. Peak load coverage with gas always performs better than with oil, with biomethane having the largest effect for GWP and FRS, thus reducing the base case by 20.4% for GWP and 17.6% for FRS. For TE, the reduction by gaseous energy materials is the highest, with natural gas performing slightly better than biomethane with a reduction of 49.4%. The mixed scenario 90NG10BM was investigated, since a supply of pure biomethane from the gas pipelines is unrealistic due to the limited capacity of producing biogas sustainably [21]. Even if the biomethane share is low, significant reductions can still be achieved.

These findings show that deep geothermal heat plants are able to comply with the threshold of 100 g CO_2/kWh by the [3]. Additionally, it also proves the potential of the choice of auxiliary energy in terms of electrical energy mix and peak load coverage to effectively reduce the environmental impact and thus meet the objectives of ongoing GWP reductions until 2050 of the Technical Expert Group. This could be used as incentive for the operators to switch to electricity contracts with renewable sources to further decrease the GWP and FRS.

In future work the potential of peak load coverage other fuels and technologies will be considered. For example in [21] there were also scenarios considered in which the gas demand is covered mainly by e-methane and hydrogen. It would be interesting to investigate these fuels as a basis for peak load. Additionally, other peak load technologies that are not based on fuels should be considered like electric boilers, high-temperature heat pumps or thermal storages.

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Additionally more impact categories as suggested in [6] can be considered, especially regarding biodiversity which is also a pressing issue alongside climate change.

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Appendix

This study is an extension of [9]. A correspondingly comprehensive LCI of the heat project can be taken from there. In the following, only the modifications are listed in Table 7 and Table 8. The latter also lists the different chosen inputs for the peak load scenarios from section 3.2.

Table 7. Changes to the LCI in comparison to [9].

Parameter	Description	Unit	Value	Source
Plastic sheath pipes	Steel, low-alloyed and drawing of pipes	kg/m DHN	15.27	[22]
	Polyethylene, high density and extrusion, plastic pipes	kg/m DHN	4.43	[22]
	Polyurethane, rigid foam	kg/m DHN	4.01	[22]
	Tap water	kg/m DHN	17.68	[22]
	Sand	kg/m DHN	243.34	[22]
Trench work	Welding: argon, liquid	g/m DHN	30.93	[23]
	Welding: diesel, burned in diesel-electric generating set	MJ/m DHN	2.22	[23]
	Bitumen adhesive compound, hot	kg/m DHN	213.16	[23]
	Diesel, burned in building machine	MJ/m DHN	270.68	[23]
	Waste asphalt	kg/m DHN	149.52	[23]
Transport	Transport, freight, lorry >32 metric ton	tkm/m DHN	51.34	[23]

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Table 8. LCI inputs for peak load coverage.

Parameter	Description	Unit	Value	Source
Cruide oil/natural gas boiler	Aluminium, cast alloy	kg	557.05	[18,24]
	Steel, chromium steel 18/8, hot rolled	kg	24880.17	[18,24]
	Stone wool, packed	kg	716.63	[18,24]
	Electricity, medium voltage	kWh	15430.77	[18]
	Heat, district or industrial, natural gas	MJ	88138.46	[18]
	Heat, district or industrial, other than natural gas	MJ	46553.85	[18]
	Transport, freight, lorry 16-32 metric ton, euro3	tkm	1307.69	[18]
	Transport, freight train	tkm	15692.31	[18]
	Transport, freight, lorry 7.5-16 metric ton, euro3	tkm	1307.69	[18]
Oil storage and catch basin	Oil storage, 3000l	p	140.60[a]	[18]
	Transport, freight, lorry 16-32 metric ton, euro3	tkm	6896.55	[18]
	Transport, freight train	tkm	82758.63	[18]
	Transport, freight, lorry 7.5-16 metric ton, euro3	tkm	3416.82	[18]
Chimney	Chimney	m/kWh[b]	1.32E-07	[18]
	Transport, freight, lorry 16-32 metric ton, euro3	tkm/kWh[b]	6.91E-07	[18]
	Transport, freight train	tkm/kWh[b]	8.29E-06	[18]
	Transport, freight, lorry 7.5-16 metric ton, euro3	tkm/kWh[b]	3.29E-09	[18]
Heat production light fuel oil	Light fuel oil	kg/MJ[c]	2.57E-02	Operator
Heat production natural gas	Natural gas, high pressure[d]	m^3/MJ	2.87E-02	[18]
Heat production natural gas	Biomethane, high pressure[d]	m^3/MJ	2.87E-02	[18]

a: scaled to oil consumption for one year (4 GWh for 2019) according to [18]
b: scaled to total heat production through boilers according to [18]
c: MJ produced heat for peak load and redundancy, in total 81.6 GWh. Amount of fuel per MJ according to caloric values and degree of utilization
d: the natural gas grid is included proportionally in the dataset for natural gas and biomethane

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