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Deep Geothermal Energy Extraction, a Review on Environmental Hotspots with Focus on Geo-technical Site Conditions

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Abstract

Knowledge about the environmental impacts of geothermal energy is important for understanding the role this technology could play in the transition towards sustainable energy production systems. In this study 30 life cycle assessment (LCA) studies on geothermal energy plants were reviewed, focusing on the major environmental hotspots and the cause-effect relationships between the geo-technical parameters and these environmental impacts. The variability in the reported environmental impacts is explained, and a more transparent picture of the geological, design and technical factors causing these impacts is provided by triangularly evaluating the reported results based on the plant's geo-technical characteristics (such as, well depth and geofluid temperature), the life cycle inventory, and the hotspot analysis results. The study focuses on six impact indicators that have been identified as high priority for geothermal energy by the GEOENVI project, as well as the water consumption impact. The results indicate that the impacts vary in magnitude and across different life cycle phases. Apart from the type of energy conversion technology used, differences in the geological and design parameters also introduce large variability in the impact results reported in the literature. Furthermore, all the reviewed LCAs adopt a static approach. Therefore, we present a research agenda that highlights the need to perform dynamic LCAs on geothermal energy exploitation plants to consider the changing context in which these technologies are operating.

Highlights

- Environmental impacts of geothermal energy extraction vary strongly.
- Factors determining the impacts vary for different energy conversion technologies.
- Site-specific geo-technical parameters drive the environmental impacts.
- Dynamic assessment is required to accurately estimate impacts in time.

Keywords

Geothermal energy, Life cycle analysis, Environmental assessment, Environmental impacts, Renewable energy, Review, LCA

Word count

10846 (excluding title, author names and affiliations, keywords, abbreviations, table/figure captions, acknowledgments, references and appendix).

Abbreviations

Abbreviations			
GHG	Greenhouse gases	**HT (HT_c/HT_{nc})**	Human toxicity (cancer/non-cancer effects)
RES	Renewable energy sources	**AD**	Abiotic resources depletion
CF	Capacity factor	**CED**	Cumulative energy demand
CHP	Combined heat and power	**EP**	Eutrophication
LCA	Life cycle analysis	**WC**	Water consumption
GW	Global warming	**LCIA**	Life cycle impact assessment
LCI	Life cycle inventory	**NCG**	Non condensable gases
AC	Acidification	**FU**	Functional unit
FWEC	Freshwater ecotoxicity	**EGS**	Enhanced geothermal system
CED_f	Cumulative energy demand, fossil sources	**CED_{nr}**	Cumulative energy demand, non-renewable sources
GWP	Global warming potential	**LCC**	Life cycle costing
EU	European Union		

1 Introduction

The EU's climate and energy framework aims for 40% reduction in GHG emissions and 32% RES share in final energy use by 2030 [1]. The exploitation of geothermal energy can help to achieve those targets, as it is considered to cause lower global warming (GW) impact than conventional fossil sources [2]. Geothermal energy can be utilized for both heat and power production and plants can operate with high CFs as geothermal energy production is independent from seasonal and climatic conditions [3]. Previous studies have shown that the environmental impacts caused by geothermal plants can vary greatly [4,5], indicating that further research is required regarding the cause–effect relationships between the environmental impacts of geothermal energy and the site-specific conditions.

LCA is a widely used tool for the environmental assessment of products and systems, implemented numerous times on geothermal plants. Saner et al. reviewed 15 studies on the GHG emissions generated by shallow geothermal heat pump heating systems and reported that they can be 80% lower than conventional fossil-fired systems [6]. Their case study showed that the electricity consumption is responsible for the major part of the environmental burden. Also, a systematic review on 79 LCA studies on RES exploitation, 4 of which concern geothermal power plants, focus on the GHG emissions, and found that these are comparable to other RES and are mostly caused by the diesel consumed by the drilling rig [7]. Moreover, from the approximately 50 LCA studies on renewable power production reviewed in [8], only 5 regard geothermal energy and the reported environmental impacts vary widely. The authors harmonized the results leading to significant reduction in their variability. An overview of the environmental impacts associated with geothermal power production is presented in [5], in which 13 LCA studies were reviewed with a focus on the methodological choices followed in the studies. The authors also defined two reference case studies and performed an LCA. They concluded that local geological conditions strongly influence the impacts and that the main source of pollution is the on-site emissions. Additionally, LCA and environmental risk assessment studies on underground CO_2 storage, compressed air energy storage, shale gas production, and geothermal power production were reviewed in [9], with 6 studies consisting LCAs on geothermal power production. The authors found that most studies focus on the GW impact and that further research is required regarding other impacts. Furthermore, 8 LCA studies on EGS plants were reviewed in [10]. The authors found that the impacts are dominated by the well drilling and are therefore strongly dependent on the subsurface conditions. However, the introduction of advanced drilling technologies in the future would lead to much lower impacts. Also, 16 LCA studies on geothermal power production were reviewed in [4]. The authors distinguished between the different power generation technologies and focused on the methodological choices of the LCAs. They found that the LCA results are strongly dependent on the local geological conditions and the LCA methodological choices, impeding the extraction of general conclusions. A systematic report on the GHG emissions of geothermal electricity production was conducted by NREL [11], indicating that these are larger and vary more widely for flash than binary plants, due to the direct emissions of NCGs. In the GEOENVI project a panorama of environmental assessment studies on geothermal plants was conducted, which focused on the goal and scope phase of the studies [12]. Also, guidelines for LCA studies on geothermal energy were proposed [13] and simplified geothermal LCA models were constructed, using the most influential parameters identified by global sensitivity analysis [14].

Since the last review paper of 2017 [4], interest in the environmental impacts of geothermal energy production has increased (Fig. 1). In this paper, we review 30 LCA studies on deep geothermal energy production. Our aim is to provide an in-depth analysis and explain the variability of the environmental impacts reported across the different LCA studies by focusing on the environmental hotspots and the cause-effect relationships among the geo-technical parameters and the environmental impacts. Therefore, when the data are available (Table 1), we evaluate triangularly the reported results considering (a) *the plants' geo-technical characteristics*, (b) *the hotspot analyses results,* and (c) *the LCI inputs*. In order to provide more accurate results we examine the different energy conversion technologies separately. In addition to the existing reviews we also separately review LCA studies on CHP and deep geothermal heating plants for which, to our knowledge, no review has been made before.

Table 1: Information provided by the 30 reviewed studies, required for the triangular evaluation of the results. 15 studies provide all three types of information.

Study	Geo-technical characteristics	Hotspot analysis	LCI
[15,16,25–31,17–24]	X	X	X
[32–36]	X	X	
[37–39]	X		X
[40–42]	X		
[43,44]			

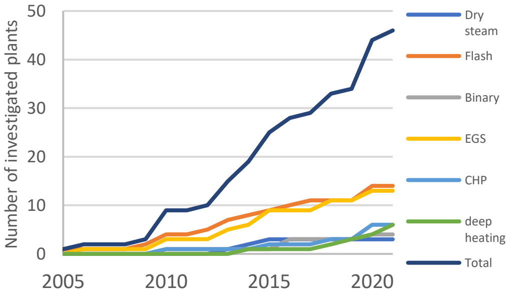

Figure 1: Chronological development of 30 geothermal LCA studies. Several studies investigate multiple plants, which explains why the sum of investigated plants is larger than 30.

2. Methods

We reviewed 30 studies published between 2005 and 2021. Ten studies investigated more than one plant. The plants were considered separately when different technologies were adopted or large geo-technical differences were present. Otherwise, the results for the different plants are presented as ranges. In total 16 real and 29 hypothetical plants were considered, mostly located in the USA, Italy, China and France (Fig. 2). The majority concern flash or EGS-binary plants.

The seven impact categories on which this review focusses are listed in Table 2. Six impact categories are identified in the GEOENVI project [13] as "high priority" for geothermal energy. We also added water consumption (WC) impact as well. The WC impact was calculated by 7 studies [15,26,28,30,32,34,37] and is considered to be of high importance for regions facing water scarcity [10]. The impact results are considered when reported in the, most frequently used, units presented in Table 2.

Three major lifecycle phases are defined: the *construction* phase including exploration and construction activities, the *operational* phase including operating and maintenance activities and the *End-of-Life (EoL)* phase, which includes processes occurring after the plant's closure (such as the wells' closure and the plant's decommissioning). The exploration activities are included in the construction phase as this is the state of the art in geothermal energy LCA studies. Of the 30 reviewed studies, 10 mention the exploration stage and assign it to the construction phase. Eight studies regard the drilling of exploratory wells [15,18,19,23,32,33,40,41], while two [24,31] consider only the fuel consumed during the seismic exploration activities, as also suggested in [13].

The different energy conversion technologies are investigated separately (dry steam, flash, binary and EGS-binary power plants, deep heating plants, CHP-flash and CHP-binary plants). For detailed descriptions of the different technologies refer to [4,45–47]. Also, LCA studies on hybrid systems (geothermal combined with other energy sources) are discussed briefly. A more thorough review of such studies should be a topic for future research.

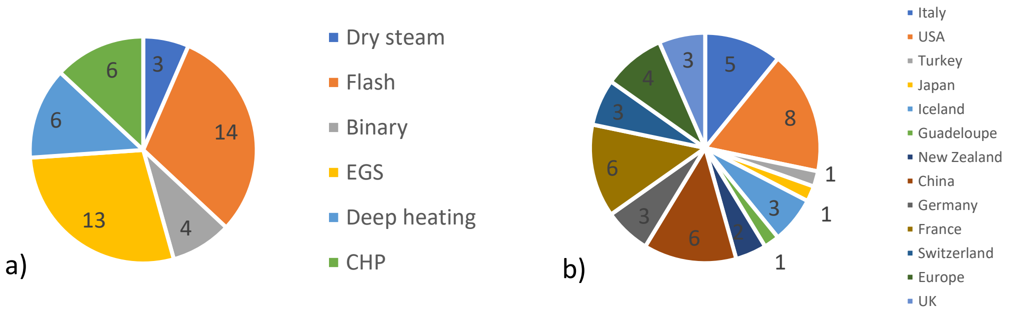

Figure 2: Plants investigated in this study: (a) type of plant, (b) location of the plant.

Table 2: Impacts investigated in this study. Impacts 1-6 are identified as "high priority" for geothermal energy [13].

Impact ID	Impact	Abbreviation	Unit
1	**Global warming**	GW	g-CO$_{2\text{-eq}}$
2	**Acidification**	AC	g-SO$_{2\text{-eq}}$
3	**Human toxicity (Cancer/Non-cancer effects)**	HT(HT$_{c/nc}$)	g-1,4 DB$_{eq}$
4	**Freshwater ecotoxicity**	FWEC	g-1,4 DB$_{eq}$
5	**Abiotic resources depletion from ultimate reserves**	AD	g-Sb$_{eq}$
6	**Cumulative energy demand fossil or non-renewable**	CED	kWh
7	**Water consumption/(resource depletion)**	WC	m^3

2.1 Reviewing process

A three-step reviewing process was followed (Fig. 3).

In *Step 1 (methodological choices and geo-technical parameters)*, the LCA methodological choices of the study (e.g., system boundaries, functional unit (FU), LCIA methods) are identified. Also, the geological conditions (such as well depth, geofluid composition and temperature) and the plant design characteristics (such as capacity, CF) reported in each study are described.

The LCA methodological choices differ across the studies. Table A1 in the appendix summarizes the most important choices for each study. The goal of each study, as mentioned by the authors, is presented in Table A2. The most frequently used FU is 1 kWh_{el} produced at the plant (Fig. A1a), while a cradle-to-grave approach is most commonly adopted (20/30 studies) (Fig. A1b). Eight studies used the CML method and the SimaPro software (Fig. A1c-d). However, the LCIA methods and the software used were reported less frequently (11 and 13 studies, respectively).

Steps 2 and 3 are complementary.

In *Step 2 (Impact results and LCI)*, the reported impacts are identified. The impacts are presented per kWh and when another FU was used they are converted if possible. Also, the LCI inputs for the lifecycle phases causing the largest impacts (identified in Step 3), are summarized. LCI data are either retrieved directly from the studies, or calculated from the reported values.

In *Step 3 (Hotspot analysis)*, the lifecycle phases and processes causing the largest environmental impact are identified, and contribution diagrams are constructed. The relative contribution values are either retrieved directly from the studies, or calculated from the reported values. When values were not reported, the study was not considered for the construction of the contribution diagrams except where mentioned explicitly.

The variability of the results reported in the studies is explained, based on the LCI inputs for the lifecycle phases causing the largest environmental impact and the differences between the geo-technical characteristics. This process constitutes the triangular evaluation (Fig. 3). The three types of information (geo-technical characteristics, LCI inputs, hotspot analysis results) are not correlated. If one of them is not provided, the results are evaluated using the available information, albeit to a more limited extent. In addition to the three abovementioned steps, the sensitivity and scenario analysis performed in the studies are investigated to further examine which parameters are the most influential regarding the environmental impacts.

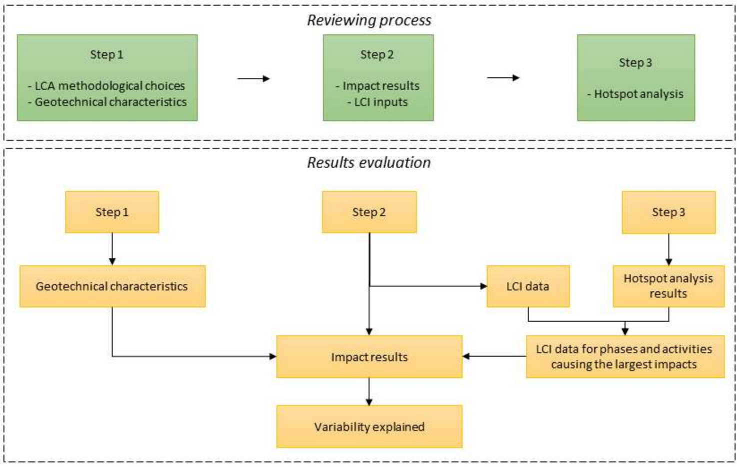

Figure 3: Reviewing process and triangular evaluation.

3. Results

The results of this review are presented by technology type. For each study the reviewing process shown in Fig. 3 is followed in order to identify the most important geo-technical factors affecting the impacts and explain the variability of the reported results across the studies.

3.1 Dry steam plants

3.1.1 Methodological choices and geo-technical parameters

One study on dry steam plants adopted a cradle to grave approach, and also evaluated the plant's sustainability in terms of resources use by emergy analysis [16]. Two other studies focused on the operational impact, using annual monitored direct emissions data, from three plants in Italy [38] and four plants in the USA [43]. Only two studies [16,38] reported geo-technical data of the plant (Table 3). Both studies investigated plants in the Tuscany region of Italy. However, the differences on the geo-technical parameters reported are large (for example, the wells are shallower in [16] which also explains the lower geofluid temperature). Also, the plant lifetimes differ. One study [16] derived the value from the plant's feasibility study, while no further information is provided in [38]. Furthermore, the direct NCG emissions reported by the two studies differ. Table 5 indicates the highly site-specific nature of the NCG emissions as they differ substantially even for plants operating in the same region (the annual CO_2 emissions reported in [38] are 2.5-4.8 times higher than in [16] (Table A3), while the median value is 3.2 times higher). Table 5 also shows that the NCGs emitted vary through time [38].

Table 3: Geo-technical characteristics of the dry steam plants investigated in the LCA studies

	Design				Geological			Output
Study	**Capacity (MW)**	**CF**	**Wells**	**Lifetime (yr)**	**Temperature (°C)**	**Depth (km)**	**Flow (t/h)**	**(GWh/yr)**
[43]	(11-725)$_{Net}$	*N.A.*	*N.A.*	*N.A.*	*N.A.*	*N.A.*	*N.A.*	*N.A.*
[38]	20	*N.A.*	10	25	300-350	2-4	*N.A.*	140-160
[16]	20	89%	8	20	238	1	80	92

3.1.2 Impact results and LCI

Table 4 summarizes the impacts reported in the studies. The GW, AC and HT impacts are mostly assessed, while information regarding the other impacts is limited. Two studies provide insight to the LCI (Table 5), one of which [16] provides the full LCI.

Table 4: Impact results for dry steam plants. The impact ranges for the three plants investigated in [38] are presented in parentheses, while the median value is noted outside of the parentheses.

	GW [g $CO_{2\text{-}eq}$/kWh]	AC [g $SO_{2\text{-}eq}$/kWh]	HT [g 1,4DB_{eq}/kWh]	AD [g Sb_{eq}/kWh]
[43]	11.4-230			
[38]	682(528-850)	3.64(0.186-12.5)	4.88(1.1-31.6)	
[16]	248	3.37	11.2	0.405

Table 5: Direct emissions of NCGs (selected substances) from dry steam plants in g/kWh. For study [38] the values refer to years 2002 to 2009, while for study [16] the values refer to data from 2007. More information in Table A3 in the appendix.

	[38]	**[16]**
Substance	Median	
CO_2	529	162
CH_4	6.96	0.94
H_2S	6.79	5.79
NH_3	2.96	1.92
As	1.6E-05	7.9E-06
Hg	1.2E-06	0.0084
H_3BO_3	0.023	0.0084

3.1.3 Hotspot analysis

One study provides information for a hotspot analysis [16] (Fig. 4). The operational phase dominates the GW, AC and HT impacts because of the NCGs direct emissions. The lubricants, steel and other material consumption assumed for the maintenance of the plant and its annual grid-electricity needs do not influence these impacts. However, they do explain the dominance of the operational phase on the AD impact. The construction phase contributes more in the HT and AD impacts because of the material consumption. The EoL phase has a minor influence on the impacts. The authors consider the diesel needs for the plant dismantling and the disposal of the materials, albeit without specifying how the materials are treated.

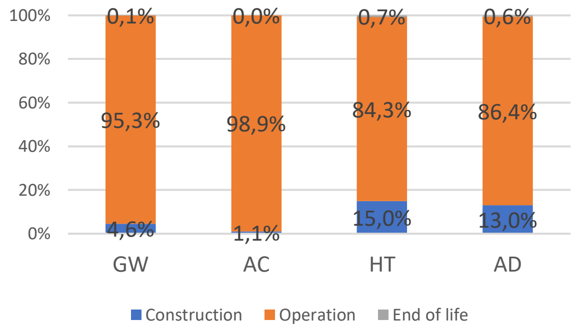

Figure 4: Hotspot analysis of the environmental impacts of dry steam plants [16]

3.1.4 Result evaluation

The hotspot analysis shows that the GW, AC and HT impacts are linked to the NCGs direct emissions occurring during the operational phase. This corresponds to the fact that the (median) GW and AC impacts reported in [38] (682 g $CO_{2\text{-eq}}$/kWh, 3.64 g $SO_{2\text{-eq}}$/kWh) are higher than those reported in [16] (248 g $CO_{2\text{-eq}}$/kWh, 3.37 g $SO_{2\text{-eq}}$/kWh) as the (median) GHG and H_2S/NH_3 direct emissions are much higher (Table 5). Accordingly, the HT impact is higher in [16] than in [38] (11.2 vs 4.88 g 1,4DB_{eq}/kWh) as the Hg emissions considered are much higher (0.084 vs 0.0000012 g 1,4DB_{eq}/kWh). The two studies investigate plants operating in an area known for the anomalously high Hg ground concentration in which Hg production was carried out in the past [48]. Thus, the exploited geofluid carries relatively high amount of Hg explaining its large direct emissions.

The above evaluation indicates that the direct emissions of NCGs drive the GW, AC and HT impacts of dry steam plants. The direct emissions are determined by the composition of the geofluid. This is influenced by highly site-specific geological factors like the rock formations and the depth and temperature of the reservoir and it can vary even among sites located in the same region. The exploitation of geothermal fields in the Mt. Amiata area results in high Hg and H_2S emissions because of the rock formations present [48]. Additionally, the exploitation of vapor-dominated reservoirs leads to higher emissions than liquid-dominated ones, while also the exploitation of reservoirs hosted by carboniferous rocks leads to higher emissions than when hosted by igneous rocks [49]. However, the final amount of NCGs released is dependent also on other parameters such as the energy conversion technology used (for example binary plants are expected to cause near zero direct emissions) and the presence or absence of abatement systems.

3.2 Flash plants

3.2.1 Methodological choices and geo-technical parameters

From the 14 flash plants investigated, six are double-flash and eight are single-flash units (Table 6). Three studies [20,40,41] excluded direct emissions from their analysis. One study [32] focused on the WC impact. The geofluid flow and temperature are scarcely reported, while data about the well depth and the design parameters are more available. Two studies reported low CFs of 60% [40] and 65% [20]. Both studies assessed hypothetical plants and made direct assumptions about the CF. The CFs reported by studies investigating real plants are close to 90% [17–19,37,41] and similar values are reported by the other studies. Also, two studies assumed a long lifetime of 100 years. This is because one study compared energy production systems and set a long lifetime for all plants, considering multiple equipment replacements, for better comparison [41], while the other study [19] used the same LCI. Also, two studies [17,37] mentioned that heat recovery takes place in the plant without reporting any information about the impacts associated with it, and are therefore included in this section.

Table 6: Geo-technical characteristics of the single and double flash plants investigated in the LCA studies. The number of production and injection wells are mentioned in parentheses. Study [20] investigates two plants. Studies [41] and [19] investigated the same plant, which is a single flash multi-unit plant, equipped with a binary unit of 15 MW.

			Design				**Geological**		**Output**
Study	**Type**	**Capacity (MW)**	**CF**	**Wells**	**Lifetime (yr)**	**Depth (km)**	**Flow (t/h)**	**Temp (^{o}C)**	**(GWh/yr)**
[40]	Double	55	60%	21-(14+7)	30	1-1,5	*N.A.*	*N.A.*	*N.A.*
[41]	Single	$(157_{flash}+15_{binary})_{Net}$	93%	61-(55+6)	100	*N.A.*	*N.A.*	*N.A.*	1430
[20]-1	Double	16_{Net}	65%	16-(8+8)	30	0.3	450	160	*N.A.*
[20]-2	Single	0.225_{Net}	65%	1	30	0.8	230.4	91	*N.A.*
[43]	Single	$(21\text{-}153)_{Net}$	*N.A.*	*N.A.*	*N.A.*	*N.A.*	*N.A.*	*N.A.*	*N.A.*
[38]	Single	20	*N.A.*	11-(7+4)	25	2-4	*N.A.*	300-350	~170
[42]	Single	30	*N.A.*	*N.A.*	*N.A.*	*N.A.*	*N.A.*	*N.A.*	250
[37]	Single	18_{Net}	96%	7-(5+2)	30	3.8	130	196	151.2
[17]	Double	210	87%	64-(47+17)	30	2.15	*N.A.*	*N.A.*	*N.A.*
[18]	Double	15.75	83%	4-(4+0)	30	>0.5	*N.A.*	230-300	95
[19]	Single	$(157_{flash}+15_{binary})_{Net}$	93%	61-(55+6)	100	1.9	*N.A.*	*N.A.*	1430
[34]	Single	50_{Net}	90%	35-(25+10)	25	3.23	*N.A.*	*N.A.*	*N.A.*
[33]	Double	50_{Net}	95%	*N.A.*	30	4-6	*N.A.*	175-300	*N.A.*
[32]	Double	50_{Net}	95%	*N.A.*	30	4-6	*N.A.*	175-300	*N.A.*

3.2.2 Impact results and LCI

The GW and AC impacts are most frequently assessed (Table 7). Studies excluding direct emissions [20,40,41] reported relatively low impacts, while the other studies report very wide impact ranges. Two studies investigating the same plant reported different GW impact, 5.6 and 118 g $CO_{2\text{-}eq}$/kWh in [41] and [19] respectively, because the former excluded the direct emissions and the latter included them. Four studies reported the direct emissions (Table 8); of these two used on-site monitored data [18,38], one used literature data [19] and only one reported the actual NCG composition [37]. Also, four studies provided the constructions phase's LCI [17–20].

Table 7: Impact results for flash plants. The impact ranges for the three plants investigated in [38] are presented in parentheses, while the median value is noted outside of the parentheses.

Study	GW [g $CO_{2\text{-eq}}$/kWh]	AC [g $SO_{2\text{-eq}}$/kWh]	HT [g $1{,}4DB_{eq}$/kWh]	FWEC [g $1{,}4DB_{eq}$/kWh]	AD [g Sb_{eq}/kWh]	CED [kWh/kWh]	WC [m^3/kWh]
[40]	15						
[41]	5.6					0.026	
[20]-1	3.88	0.03					
[20]-2	11.8	0.057					
[43]	21-438						
[38]	381-1040 (702)	7.18-44.8 (17.1)	1.16-3.43 (3.13)				
[42]	63	8.75	1	0.002	5.0E-6		
[37]	477	2.27	1.89_{HTc}, 28_{HTnc}	2.1			0.16
[17]	35-45					$(0.1\text{-}0.2)_{nr}$	
[18]	47	1.95			3.71E-8	0.023_{nr}	
[19]	118	0.40		13.1		0.0055_{f}	
[34]	245						4.97E-5
[33]	103						
[32]							0.00015

Table 8: Direct emissions of NCGs (selected substances) from flash plants in g/kWh. For study [38] the values refer to the median value from data referring to 2002-2009 and more information is provided in Table A4 in the appendix. For study [37] the NCGs concentration on the geofluid is 4% w/w resulting in direct emissions of 5100 kg-CO_2/h, 0.4 kg-CO/h, 79 kg-CH_4/h, 90 kg-H_2S/h, 11.6 kg-NH_3/h, 0.0056 kg-Hg/h and 0.042 mg-As/$l_{exploited}$.

	[37]	**[38]**	**[19]**	**[18]**
Substance		Median		
CO_2	255	398	83	41.6
CO	0.02	0.0375	N.A.	N.A.
H_2S	0.92	1.53	N.A.	1.02
CH_4	3.965	9.81	0.75	0.00326
NH_3	0.075	14.1	0.06	N.A.
Hg	5.5E-5	1.03E-06	0.004	N.A.
As	1.4E-7	1.20E-06	N.A.	N.A.
SO_2	N.A.	N.A.	0.158	N.A.
Ni	N.A.	6.88E-07	N.A.	N.A.
Cr	N.A.	2.83E-07	N.A.	N.A.

3.2.3 Hotspot analysis

3.2.3.1 Excluding direct emissions

A hotspot analysis is performed for the two plants investigated in [20] using the reported impact values. The construction phase dominates the GW and AC impacts (Fig. 5a). The authors assume that 2% of the initial steel quantity is replaced annually and that 50 kg-diesel/$MW_{instaled}$ are required annually for the plant's maintenance. These assumptions explain the relatively high contribution of the operational phase to the impacts, despite the exclusion of the direct emissions. The EoL phase includes the material and energy required for sealing the wells, the plant decommissioning, the environmental impacts of which are assumed to be 10% of the construction and operational impacts, and the disposal of the waste. These lead to the EoL phase causing about 10% of the total impacts. The construction impacts are dominated by the wells' development. Also, the steel and copper consumed for the manufacturing of the equipment and the building construction contribute considerably (Fig. 5b). Steel and diesel consumption cause 55% and 42% of the GW and AC impacts respectively. The other two studies excluding direct emissions identify the operational phase to dominate the impacts because of the consideration of multiple equipment replacements and make-up well drillings [40,41].

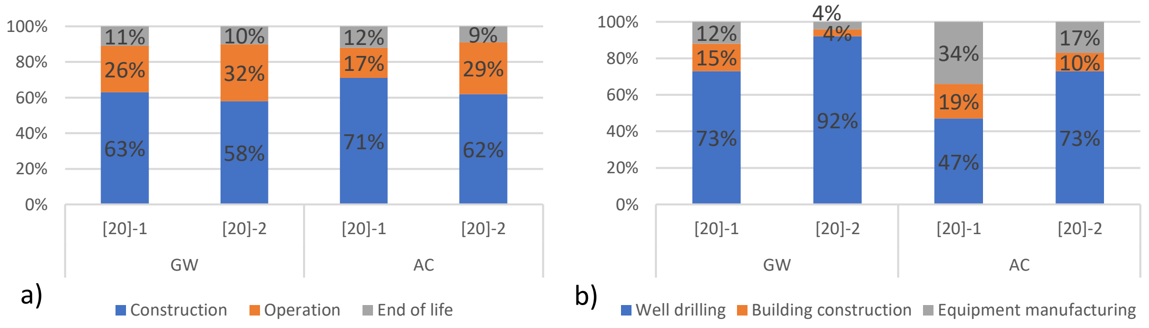

Figure 5: Hotspot analysis of the environmental impacts of flash plants excluding direct emissions. a) Lifecycle, b) Construction phase

3.2.3.2 Including direct emissions

Five studies provide information for a hotspot analysis [17–19,33,34]. The operational phase dominates the GW impact due to direct GHG emissions (Fig. 6a), while the wells' development dominates the construction GW impact (Fig. 6b). Also, one study reported that 1.3% of the GW impact is caused by the transmission network construction [34]. Also, one study found that the AC, HT and FWEC impacts are dominated by the direct emissions (>98%) and the CED_f impact by the wells development (>90%) [19]. Another study [18] reported similar findings for the AC and CED impacts, although it attributed the HT impact to the construction phase as no direct emissions of metals were reported.

Only one study considered operational activities other than the direct emissions (study [18] which considers the drilling of 1.1 make-up wells), while another study mentioned that such activities should be included [17]. A study compiling the detailed LCI of the Helisheidi double flash CHP plant [50] includes in the maintenance activities of the plant the drilling of make-up wells, the installation of new pipelines, the consumption of groundwater for adjusting the PH of the geofluid and for regular cleaning, the consumption of various chemicals (such as lubricants and salt) for machinery maintenance and anti-scaling purposes and the replacement of equipment. Similar maintenance activities are reported in [37,51].

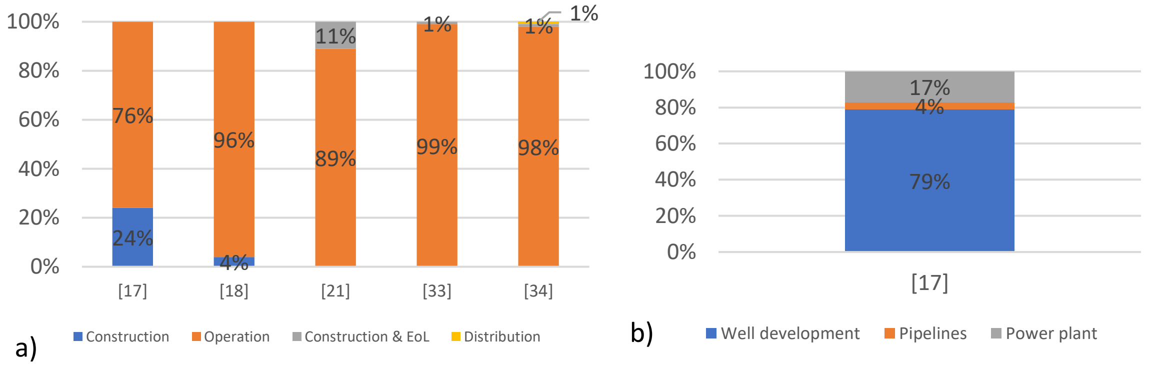

Figure 6: Hotspot analysis of the global warming impact of flash plants including direct emissions: (a) lifecycle, (b) construction phase

3.2.4 Result evaluation

3.2.4.1 Excluding direct emissions

One study provides the required information for the triangular evaluation [20]. The hotspot analysis showed that the GW and AC impacts are mostly caused by the materials and energy consumed for the development of the wells. Low GW and AC (3.88 g $CO_{2\text{-eq}}$/kWh, 0.03 g $SO_{2\text{-eq}}$/kWh) impacts are reported for the high-capacity double-flash unit considering low reservoir depth and low materials and energy consumption for the wells' development (100 kg_{steel}/m and 2.4 GJ_{diesel}/m). Higher impacts are reported for the low-capacity single-flash unit where the depth drilled is larger in relation to the installed capacity (Table 6). The low CF and large number of deep wells result in a relatively high GW impact of 15 g $CO_{2\text{-eq}}$/kWh in [40], while the large plant capacity and CF and the long lifetime assumed in [41] result in a low GW impact of 5.6 g $CO_{2\text{-eq}}$/kWh. Also, one study showed, through sensitivity analysis, that larger CF and lifetime lead to lower impacts as the total power output is increased [40].

3.2.4.2 Including direct emissions

Three studies provide the required information for the triangular evaluation [17–19], while another five studies provide two out of the three types of information required [32–34,37,38].

The hotspot analyses indicate that the GW, AC, HT and FWEC impacts are mainly caused by the NCG direct emissions. Indeed, the low GHG and H_2S/NH_3 direct emissions reported in [18] (Table 8) result in low GW and AC impacts (47 g $CO_{2\text{-eq}}$/kWh, 0.4 g $SO_{2\text{-eq}}$/kWh). In contrast, the relatively high direct emissions in [19] lead to high GW and AC impacts (118 g $CO_{2\text{-eq}}$/kWh, 1.95 g $SO_{2\text{-eq}}$/kWh). In [38], the substantially high direct emissions of GHG and H_2S/NH_3 (Table 8) lead to very high GW (702 g $CO_{2\text{-eq}}$/kWh) and AC impacts (17.1 g $SO_{2\text{-eq}}$/kWh), while similar observations are extracted in [37]. Limited information is present regarding the HT and FWEC impacts. One study attributes these impacts to direct emissions of metals [19]. A relatively high HT impact (3.13 1,4 DB_{eq}/kWh) is reported in [38]. According to the authors the HT impact is mainly caused by direct emissions of Hg, H_2SO_4, H_3BO_3, As and Sb. Meanwhile, a study that did not report emissions of Ni or Cr found a low HT impact [37] (Tables 7-8). Another four studies attributed the GW impact to GHG direct emissions [17,33,42,43]; one of these also attributed the AC, HT and FWEC impacts to NCG direct emissions [42]. In addition, the scenario analysis performed in [37] shows that reducing the direct emissions, through abatements systems, or considering a part of them to be natural leads to much lower GW and AC impacts. Furthermore, the sensitivity analysis in [34] identified the geofluid's composition in NCGs, which determines the direct emissions, as the most influential parameter regarding the GW impact.

The hotspot analyses also show that the materials and energy consumed for the development of the wells dominate the CED and AD impacts. The high energy needs for drilling (1098 GJ_{diesel}/MW) in [17] lead to a high CED_{nr} impact (0.1-0.2 kWh/kWh). Low CED impacts (0.0055-0.023 kWh/kWh) were reported by two other studies [18,19], reporting lower energy needs (36 and 93 GJ_{diesel}/MW). The difference between the reported energy needs is explained by the large number and depth of wells – in relation to the capacity, considered in [17]. The drilling needs are also dependent on the rock formations and the drilling techniques used, for which no information is available. The energy needs mentioned were calculated from the provided LCIs.

Three studies calculated the WC impact. A relatively large WC impact was reported in [37] without further explanation being provided. In contrast, a WC impact of four magnitudes lower was reported in [34] mostly attributed to the groundwater losses during the flashing process. Finally, [32] reported a 3 times higher WC impact than that in the previous study, attributed mostly to the cooling system needs. If the geofluid lost during the flashing process is replaced, then the reported WC impact is about 65 times higher than in the case it is not replaced.

The above observations indicate that the GW, AC and HT impacts of flash plants are dominated by the direct emissions of NCG as in dry steam plants. However, much more information is available for flash plants. The direct emissions are determined by the geofluid's composition which is discussed in Section 3.1.4.

The CED and the AD impacts, and also the GW and AC impacts when direct emissions are excluded, are driven by geo-technical parameters that determine the total power output (such as the temperature, capacity, CF, flow and lifetime) and the energy and material consumption (number and depth of wells, material need for drilling). Thus, variations in these parameters introduce variability in the impact results. Higher temperatures and flows lead to higher plant capacities and, depending on the CF, to higher energy output, so the per kWh impacts are reduced. In contrast, larger reservoir depth and number of wells lead to higher material and energy consumption which increases the impacts.

3.3 Binary-ORC plants

3.3.1 Methodological choices and geo-technical characteristics

The 24 scenarios of different binary-ORC configurations investigated in [39] show that cycles with higher efficiency (such as supercritical cycle) and the usage of low-GWP working fluids (for example, R1234yf, isobutane) instead of high-GWP working fluids (for example, R134a, R245fa) lead to lower impacts. Another study indicated that using low-GWP working fluids lead to lower impacts despite the slightly reduced energetic efficiency their usage induces [52]. Kalina cycles present higher efficiency than ORC for low-temperature fields [53,54]. However, they require more machinery and the usage of NH_3. LCA comparisons should be performed to identify the cycle causing lower impacts. All three studies refer to hypothetical plants and use a lifetime of 30 years (Table 9). The reported CF varies and its selection is either based on literature values [39] or is not discussed [20,33]. The installed capacity is relatively low and doublets are usually drilled (Table 9).

Table 9: Geo-technical characteristics of the binary plants investigated. WFL refer to annual working fluid losses. Doublet refers to one production and one re-injection well

	Design					Geological		
Study	**Cap (MW)**	**CF**	**Wells**	**Lifetime (yr)**	**WFL**	**Flow (lt/s)**	**Temp (°C)**	**Depth (km)**
[39]	3.6-6.7	80%	Doublet	30	2%	98-141	127-155	3.5-3.9
[33]	10_{Net}	95%	*N.A.*	30	*N.A.*	*N.A.*	175-300	<2
[20]	0.15_{Net}	65%	Doublet	30	2%	33	110	3.2

3.3.2 Impact results and LCI

The reported GW impact range widely, while using high-GWP working fluids results to higher GW impact (Table 10). Also, one study reported a relatively high GW impact [20]. In contrast, low variability is observed for the AC and CED impacts. Two studies [20,39] provide LCI insight.

Table 10: Impact results for flash plants. The global warming impact reported in parentheses for [39] includes the scenarios using working fluids with high GWP.

Study	GW [g $CO_{2\text{-}eq}$/kWh]	AC [g $SO_{2\text{-}eq}$/kWh]	CED_{nr} [kWh/kWh]
[39]	13.2-23 (15.6-130.1)	0.104-0.18	0.05-0.087
[33]	5.7		
[20]	80.5	0.25	

3.3.3 Hotspot analysis

Hotspot analysis is performed for one study [20]. The GW and AC impacts are dominated by the construction phase, which is driven by the wells' development (Fig. 7a-b). The operational and EoL phases also contribute to the impacts, because of the assumptions made (discussed in Section 3.2.3.1) and the consideration of 2% annual working fluid leakage (Table 9). The working fluid's lifecycle causes 41% and 14% of the GW and AC impacts respectively. The impacts caused during the wells' development are dominated by steel and diesel consumption.

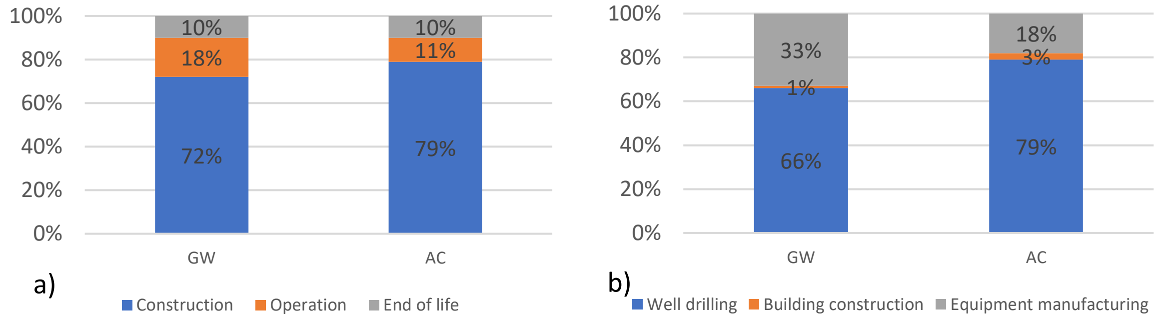

Figure 7: Hotspot analysis of the environmental impacts of binary plants [20] , (a): lifecycle, (b): construction phase.

3.3.4 Result evaluation

The hotspot analysis shows that the GW and AC impacts are driven by the construction phase and more specifically by the development of the wells. The material and energy needs reported in [20] for the wells' development, are relatively low (100 kg_{steel}/m and 2.4 GJ_{diesel}/m). However, the low plant capacity and CF, the large well depth and the working fluid leakage lead to high GW and AC impacts (80.5 g $CO_{2\text{-}eq}$/kWh, 0.25 g $SO_{2\text{-}eq}$/kWh). Wide GW variability (13.2-130.1 g $CO_{2\text{-}eq}$/kWh) is reported in [39]. The leakage of high-GWP working fluids cause high GW impact. When the scenarios using high-GWP working fluids are excluded, the maximum GW impact is relatively low (23 g $CO_{2\text{-}eq}$/kWh), as the high plant capacity and CF compensate for the high diesel needs for drilling (7.4 GJ_{diesel}/m). Also, high capacity and CF result in a very low GW impact of 5.7 g $CO_{2\text{-}eq}$/kWh in [33]. Similar observations are extracted for the AC and CED_{nr} impacts although these are not affected by the working fluid.

In binary-ORC plants geo-technical parameters determining the power output and the total material consumption drive the impacts. Higher capacity and CF lead to higher power output and to lower per kWh impacts. The capacity is determined by the geofluid's temperature and flow rate, both of which depend on the reservoir conditions. Also, larger reservoir depth leads to increased drilling impacts, while the rock formations present also influence the material and energy requirements for the drilling. Moreover, if a high-GWP working fluid is used, its leakage can cause high GW impacts.

3.4 EGS-binary power plants

3.4.1 Methodological choices and geo-technical characteristics

The reported capacities for EGS-plants are generally low (Table 11), except for two studies that investigated hypothetical plants and set the plant capacity arbitrarily [32,33] and for the high capacity scenario in [15]. The CFs reported by the studies range from 80 to 97%. One study, that investigated a hypothetical plant, assumed a low CF of 65% [20]. The lifetime of the plant varies among the studies. One study used lifetimes of 20 and 30 years for different scenarios based on the expected lifetime of the wells [15]. A lifetime of 25 years was reported in [24] based on the expected lifetime of the plant. The other studies assume similar lifetimes either based on literature values [22,23,36] or making assumptions [21,32,33] that are not explained further. Table 11 shows that mostly doublets or triplets of relatively deep wells are drilled. Design characteristics are more frequently reported than geological characteristics.

Table 11: Geo-technical characteristics of the EGS-binary plants investigated in the LCA studies. Triplet refers to 1 production and 2 re-injection wells. **Production and re-injection temperature, **Study [15] provides the geothermal gradient (30, 35 and 40 °C/km for the low, medium and high capacity plants respectively).*

			Design			**Geological**		**Output**
Study	**Cap (MW)**	**CF**	**Wells**	**Lifetime (yr)**	**Depth (km)**	**Flow (kg/s)**	**Temp (°C)***	**(MWh/yr)**
[15]-1	2.9_{Net}	*N.A.*	Triplet	20	5	147	*N.A./N.A.***	*N.A.*
[15]-2	5.5_{Net}	*N.A.*	2 Triplets	30	5	147	*N.A./N.A.***	*N.A.*
[15]-3	14.6_{Net}	*N.A.*	Triplet	30	6	147	*N.A./N.A.***	*N.A.*
[21]	0.91_{Net}	80%	Doublet	30	3.8	69.4	125/60	6476
[22]	1.61_{Net}	91%	Triplet	25	4	40	165/70	12880
[23]	0.67_{Net}	90%	Doublet	30	5	21	175/90	*N.A.*
[24]-1	3.7_{Net}	97%	Doublet	25	5.7	82.5	170/66	31600
[24]-2	2.86_{Net}	97%	Doublet	25	6.9	82.5	150/66	24400
[33]	50_{Net}	95%	*N.A*	30	4-6	*N.A*	150-225/N.A.	*N.A.*
[32]	50_{Net}	95%	*N.A*	30	4-6	*N.A*	150-225/N.A	*N.A.*
[36]	36_{Net}	80%	*N.A*	20	*N.A.*	*N.A.*	*N.A./N.A.*	*N.A.*
[20]	2.8_{Net}	65%	Doublet	30	3.7	28	236/57	*N.A.*
[44]	*N.A.*	*N.A.*	*N.A.*	*N.A.*	*N.A.*	*N.A.*	*N.A./N.A.*	*N.A.*

3.4.2 Impact results and LCI

The GW and AC impacts are most frequently calculated (Table 12). The variability of results is relatively low (7.55-62 g $CO_{2\text{-}eq}$/kWh for GW), as no direct emissions occur. Six studies provided insight to their LCIs (Table 13). One study reported the usage of electric, instead of diesel-engine, drilling rigs [15].

Table 12: Impact results for EGS-binary plants. The impact values for [21] *are estimated from the figures provided in the study.*

Study	**GW [g $CO_{2\text{-}eq}$/kWh]**	**AC [g $SO_{2\text{-}eq}$/kWh]**	**HT [g 1,4DB_{eq}/kWh]**	**FWEC [g 1,4DB_{eq}/kWh]**	**AD [g Sb_{eq}/kWh]**	**CED [kWh/kWh]**	**WC [m^3/kWh]**
[15]-1	45.6	0.165	27.4	0.54			1.3E-6
[15]-2	28.9	0.1	17.4	0.34			0.8E-6
[15]-3	7.55	0.028	4.62	0.09			0.2E-6
[21]	(42-62)	(0.32-0.5)				$(0.172\text{-}0.264)_{nr}$	
[22]	36.7					0.16_{nr}	
[23]	46.7				8.6E-10		1.3E-4
[24]-1	24.73						
[24]-2	35.99						
[33]	23						
[32]							0.008-0.07
[36]	24						
[20]	12.7	0.043					
[44]	41	0.19				0.15_{f}	

Table 13: Steel and energy consumption used for the drilling of the wells in EGS-binary plants

Study	**Steel consumption (kg/m)**	**Diesel consumption (GJ/m)**	**Electricity consumption (kWh/m)**
[33]	309	0.1	3932
[21]	103	7.5	*N.A.*
[22]	111	4	*N.A.*
[23]	84.3	7.2	*N.A.*
[24]	95-130	4.2-5.8	23
[20]	100.2	2.4	*N.A.*

3.4.3 Hotspot analysis

Hotspot analysis (Fig. 8-10) is performed for four studies [20,21,23,24]. Two studies found the well development dominated the GW impact [21,23], considering the pumps' replacement, the filters' disposal and the water use for the plant's maintenance. Similar results were reported by four other studies [15,22,33,36]. By contrast, a study including the consumption of water, chemicals, salt and oil for maintenance purposes, an annual working fluid leakage of 0.5%, the transportation of the maintenance employees and CO_2 emissions emerging when the geofluid is not moving during the plant's maintenance reported that the operational phase contributes 11-13% to the GW impact [24]. The operational phase causes 24% of the GW impact in [20] because of the maintenance activities assumed (section 3.3.3). The latter two studies considered large material consumption for the surface constructions leading to their increased contribution to the GW impact. Steel and diesel consumption dominate the GW impact in [23] while in [20] it is driven the working fluids' lifecycle (Fig. 8b). Similar results were shown for the AC impact (Fig. 9a-b), while the CED, FWEC, HT and AD impacts are dominated by the steel and diesel consumption during the development of the wells (Fig. 10) [23] [21].

Two studies attributed the WC impact to the wells' development [15,23]. A study focusing on the WC impact found that it is dominated by water losses to the enhanced reservoir's surrounding environment during the operational phase [32].

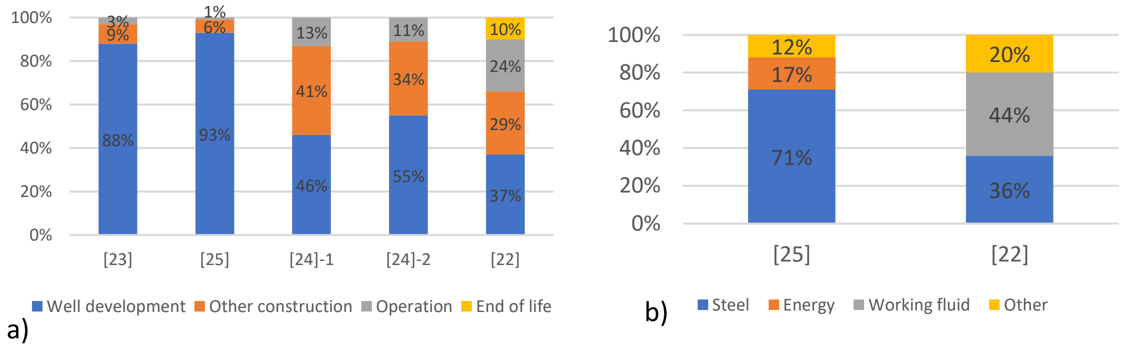

Figure 8: Hotspot analysis of the global warming impact of EGS-binary plants. a) by lifecycle phase. b) by material consumption, "other" refers to every other material used.

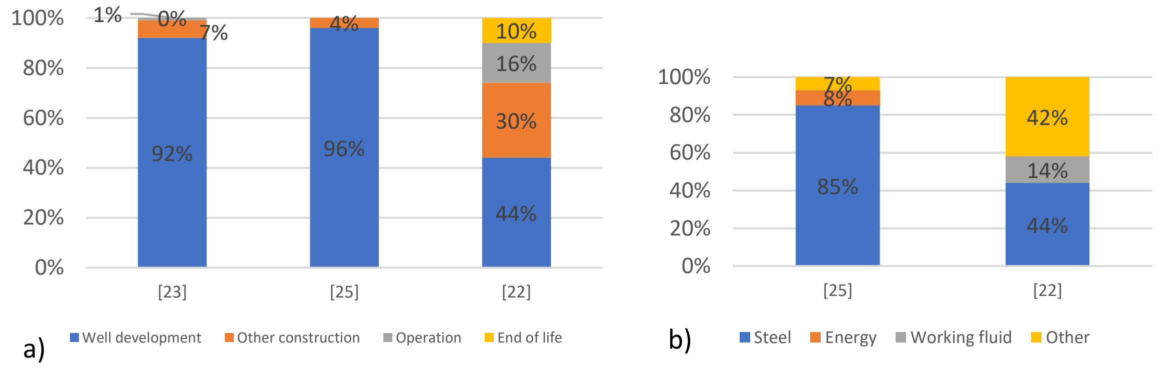

Figure 9: : Hotspot analysis of the acidification impact of EGS-binary plants. a) by lifecycle phase. b) by material consumption, "other" refers to every other material used.

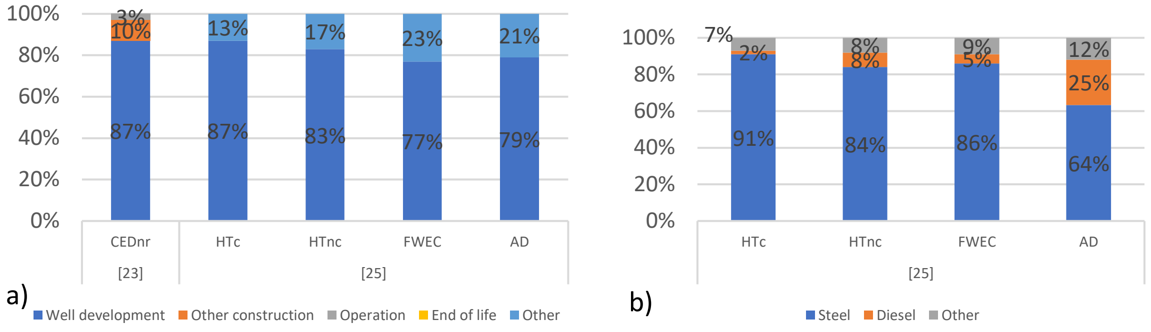

Figure 10: Hotspot analysis of the environmental impacts of EGS-binary plants, a) by lifecycle phase, "other" refers to every other process except for wells development. b) by material consumption, "other" refers to every other material used.

3.4.4 Result evaluation

The hotspot analyses reveals that the impacts are mainly caused during the construction phase predominantly due to steel and diesel consumed during the development of wells. The relatively high plant capacity and the use of electric rigs, reported in [15], lead to low GW and AC impacts (7.55 g $CO_{2\text{-eq}}$/kWh, 0.028 g $SO_{2\text{-eq}}$/kWh), despite the deep triplet drilled and the high steel casing needs (309 kg_{steel}/m) (Tables 11-13). The medium and low capacity units cause higher impacts because of the second triplet drilled and the lower plant lifetime respectively but also because of the lower capacity. Relatively high GW and AC impacts (62 g $CO_{2\text{-eq}}$/kWh, 0.42 g $SO_{2\text{-eq}}$/kWh) are reported in [21] for a plant with low capacity and CF and high diesel needs for drilling (7.5 GJ/m). Meanwhile, the low diesel consumption considered in [20] (2.4 GJ/m) and the relatively high capacity lead to low GW and AC impacts (12.7 g $CO_{2\text{-eq}}$/kWh, 0.04 g $SO_{2\text{-eq}}$/kWh). A low GW impact (37 g $CO_{2\text{-eq}}$/kWh) is found in [22] as the CF is high, the depth is relatively low and low energy drilling needs are reported. Similarly, [24] reports low GW impact (24-36 g $CO_{2\text{-eq}}$/kWh) despite the large depth and the relatively low lifetime, because of the high plant capacity and CF and the low steel and diesel needs for drilling. Finally, high diesel consumption and low capacity leads to a high GW impact (46.7 g $CO_{2\text{-eq}}$/kWh) in [23]. Information regarding the HT, FWEC, CED and AD impacts is limited. However the hotspot analyses show that they are determined by the same factors as the GW and AC impacts, thus similar observations are expected. By contrast, the WC impact is reported to be caused by a variety of factors, so no conclusions are extracted.

The results for EGS-binary power plants are similar to those of binary plants. The major sources of variability are differences in the geo-technical parameters affecting the material and energy consumption and the power output. The capacity, and therefore the power output, is determined by geological parameters such as the temperature and the flow of the geofluid which vary greatly for different geological settings and lithologies. Also, the energy and material needs for drilling are largely determined by geological characteristics such as the reservoir's depth and the rock formations present. The sensitivity analysis performed in [21] found that the temperature has the largest influence on the impacts as it determines the plant capacity. Also, other parameters affecting the power output (CF, lifetime, ORC efficiency, specific heat capacity of the geofluid) are found to affect the impacts significantly as does the reservoir's depth. Similar results were reported in the sensitivity analysis performed in [15], while increasing the lifetime was also found to have a positive effect on the impacts in [24].

3.4.5. Seismicity

Geothermal development causes modifications in the underground reservoir and thus bares the risk of induced seismicity [5]. The risk is higher for EGS plants as their development requires intensive stimulation of the reservoir, which induces large pressure differences [53]. A number of EGS projects have been stopped due to induced seismicity events [46]. The quantification of induced seismicity risk in the LCA context has not been greatly developed [5]. Only one of the reviewed studies tackled this issue, using a four-grade scale, based on the model of [55], to assess the potential seismic risk [22]. The authors found that the risk of seismic events increases for higher flow, and thus higher capacity.

3.5 Deep geothermal heating systems

3.5.1 Methodological choices and geo-technical characteristics

The information reported regarding the geo-technical characteristics of deep geothermal heating plants is limited (Table 14). One study compared the performance of two different borehole heat exchanger designs (butted vs coaxial) [31] and only the better-performing one was considered in this study (butted). Two studies [24,29] considered the construction of the distribution network. Two studies considered a lifetime of 25 years based on the expected lifetime of the real plant investigated [24] or without providing further information [31]. By contrast, [25] used a lifetime of 30 years, derived from the plant's feasibility analysis, [29] did so without providing further information and [30] did so based on the GEOENVI guidelines [13].

*Table 14: Geo-technical characteristics of the deep geothermal heating plants investigated in the LCA studies. *All plants utilize a doublet. **The two studies investigate the same plant.*

	Design			Geological			Output
Study	**Capacity (MW)**	**Distance to demand (km)**	**Lifetime (yr)**	**Depth (km)***	**Temp (°C)**	**Flow (kg/s)**	**(GWh/yr)**
[29]	*N.A.*	4-5	30	*N.A.*	85	*N.A.*	*N.A.*
[25]	2.5	*N.A.*	30	2	*N.A.*	*N.A.*	13.14
[24,30]**	25	15	25	5.7	170	70	180
[26]	*N.A.*	*N.A.*	*N.A.*	1.4	*N.A.*	27	*N.A.*
[31]	1.1-1.3	*N.A.*	25	2-3	*N.A.*	*N.A.*	*N.A.*

3.5.2 Impact results and LCI

All studies assessed the GW impact, while the other impacts were scarcely addressed (Table 15). Two studies reported relatively high GW impact [23,79]. Also, two studies investigating the same plant reported different GW impact because one [30] followed the GEOENVI guidelines and the other did not [24]. The electricity mixes assumed to supply the plants vary (Table 16). Three studies [24,25,30] provide insight to the construction LCI.

Table 15: Impact results for deep geothermal heating plants.

Study	**GW** [g $CO_{2\text{-eq}}$/kWh]	**AC** [g $SO_{2\text{-eq}}$/kWh]	**CED$_{nr}$** [kWh/kWh]	**HT** [g 1,4DB$_{eq}$/kWh]	**FWEC** [g 1,4DB$_{eq}$/kWh]	**AD** [g Sb$_{\text{-eq}}$/kWh]
[29]	5.8	0.029	0.028	11.9	3.6	0.048
[25]	9.7-14					
[24]	6.97-9.15					
[26]	188	0.36				
[31]	59.4					
[30]	3.77					4.6E-5

Table 16: Electricity mixes supplying the deep geothermal plants investigated in the LCA studies.

Study	**Electricity mix**
[29]	Renewables
[25]	High share of natural gas and other fossils. 190 g $CO_{2\text{-eq}}$/kWh
[24]	50.3% nuclear, 45% hydro, 3.6% coal, 0.6% PV. 47 g $CO_{2\text{-eq}}$/kWh
[26]	Coal-dependent
[31]	Highly coal dependent. 481.3 g $CO_{2\text{-eq}}$/kWh
[30]	66% nuclear, 6% fossils, 28% RES

3.5.3 Hotspot analysis

The operational phase dominates the GW impact in [26], because the pumping needs of the plant are met by a coal-dependent electricity mix causing large impacts (Fig. 11a). In contrast, the wells' development drives the GW impact in [25], with the contribution of the operational phase varying depending on the pumping needs (14 KW pumps in the base case and 56 KW pumps in the case noted by *). Also, the well development dominates the GW impact in [31] followed by the electricity consumed during the operation. The construction of the distribution network causes most of the GW impact in [24] due to the large distance to the demand (15 km), while the wells' development and the plant operation also contribute considerably. For the same plant, a study that did not include the construction of the distribution network found that the well drilling drove the GW impact along with other construction activities and the electricity consumed during the plant's operation [30]. The wells' development and the distribution network construction also dominate the GW impact in [29]. The GW impact of wells' development is driven by the steel and diesel consumed [24,25,29] (Fig. 11b).

One study found that the plant's pumping needs drive the AC and FWEC impacts, also identifying that the wastewater treatment activities cause large FWEC impact [26]. Additionally, the AC, FWEC, HT, AD and CED impacts are dominated by the wells development in [29].Furthermore, the WC, AD, HT and AC impacts are mostly attributed to the construction phase (well development and machinery manufacturing) in [30], while the FWEC is reported to be driven by the electricity consumed during the operational phase.

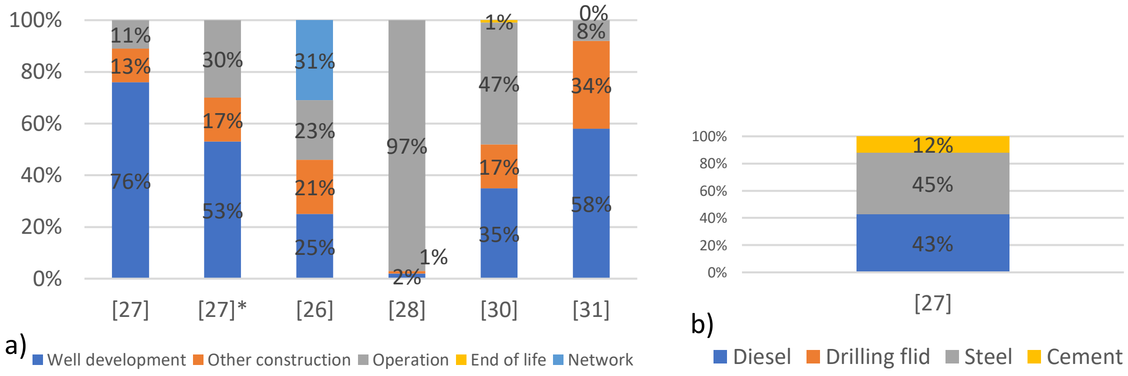

Figure 11: Hotspot analysis of the global warming impact of deep geothermal heating plants. a: Lifecycle, b: Development of wells. The values shown for [26] are estimated from the figures provided in the study. The values for [25] refer to the 14 KW pumps case while the [25] refers to the 56 KW pumps case.*

3.5.4 Result evaluation

High GW and AC impacts (188 $CO_{2\text{-eq}}$/kWh, 0.36 $SO_{2\text{-eq}}$/kWh) are reported in [26], dominated by the electricity consumed during the operational phase because of the coal-dependent electricity supplying the plant.

For less carbon-intensive electricity mixes, the impacts are driven by construction activities. A high GW impact (59.4 g $CO_{2\text{-eq}}$/kWh) was reported in [31] because of the low plant capacity and CF (120 days of operation annually) but also because the plant is supplied by a highly coal-dependent electricity mix leading to high operational GW impact. A lower GW impact (9.7-14 g $CO_{2\text{-eq}}$/kWh) was found in [25], dominated by the development of wells because of the, reported, large steel and energy needs for the drilling, and of the low heat output (Table 14). By contrast, low drilling needs were reported in [24], for the Rittershoffen plant, (4.2 GJ_{diesel}/m, 97 kg_{steel}/m), which combined with the high heat output led to relatively low GW impact (6.97-9.15 g $CO_{2\text{-eq}}$/kWh), despite the construction of the distribution network. The GW impact of the Rittershoffen was estimated to be even lower in [30] (3.77 g $CO_{2\text{-eq}}$/kWh), in which the heating network is excluded, the assumed lifetime is longer (Table 15) and the electricity mix assumed to supply the plant is less fossil-dependent. Also, low GW impact is reported in [29], assuming minimal operational impacts due to the RES-dominated electricity mix, mainly caused by the wells' development and the construction of the distribution network. Information regarding other impacts is limited. One study calculated the WC impact, attributing it mostly to the construction phase, without providing further discussion [30].

Unlike power production plants, the impact of deep heating plants is influenced by the local electricity mix. High operational impacts are expected when the plant is supplied by fossil-dependent electricity mixes. When the electricity mix is RES-dominated these impacts are expected to be low and construction activities drive the impacts. Two studies found that supplying the plant with less carbon-intensive electricity mixes leads to GW benefits [24,26]. Also, the construction of the distribution network, when included, can cause high impacts depending on its length. Variability in the results of the studies is also introduced by differences in the parameters determining the total heat output (temperature, capacity, CF) and the materials and energy consumption for drilling (well depth). A higher CF was shown to lead to lower GW impact in [31].

3.6 CHP plants

3.6.1 Methodological choices and geo-technical characteristics

Studies have investigated both CHP-binary and CHP-flash plants, with the latter reporting higher capacities and multiple wells' drilling (Table 17). The reported CFs are generally high, except for one study [21], which assumed a 74% CF without providing further explanation. The reported plant lifetime varies among the studies. Three studies assume a lifetime of 30 years, either based on literature values [27] or without providing further explanation [21,23]. Shorter lifetime (25 years) is used by [24], based on the expected lifetime of the plant, and [35], based on literature values. Also, a long lifetime of 40 years was reported in [28], based on the expected lifetime of the plant.

*Table 17: Geo-technical characteristics of the CHP plants investigated in the LCA studies. (The number of production and injection wells are mentioned in parentheses). *MW_{el}/MW_{th}, **GWh_{el}/GWh_{th}*

		Design			**Output**		**Geological**		
Study	**Type**	**Cap (MW)***	**Wells**	**Lifetime (yr)**	**CF**	**(GWh/yr)****	**Depth (km)**	**Temp (°C)**	**Flow (kg/s)**
[27]	Flash	303/267	64(47+17)	30	87%	*N.A./N.A.*	2.15	*N.A.*	*N.A.*
[28]	Flash	61/21.1	14(8+6)	40	99%	544/32	3	*N.A.*	*N.A.*
[35]	Binary	2.9	3(2+1)	25	96%	*N.A./N.A.*	0.45-0.725	150	70
[24]	Binary-EGS	1.82/6.67	2(1+1)	25	97%	15.4/58.3	7	170	82.5
[21]	Binary-EGS	0.67/5.56	2(1+1)	30	74%	6/10	3.8	125	69.4
[23]	Binary-EGS	0.67/3.54	2(1+1)	30	90%	*N.A./N.A*	4	175	21

3.6.2 Impact results and LCI

All studies calculate the GW impact, while information about the other impacts is limited (Table 18). Five studies provide LCI insight [21,23,24,27,28] .

*Table 18: Impact results for CHP plants. The impacts are presented first for electricity and then for heat production (impact electricity/impact heat). *Studies [23] and [28] report results only for power production. We calculated the impacts of heat production using the allocation factors reported by the authors.*

Study	**AD [g Sb_{eq}/kWh]**	**GW [g CO_{2-eq}/kWh]**	**HT [g 1,4DB_{eq}/kWh]**	**AC [g SO_{2-eq}/kWh]**	**FWEC [g 1,4DB_{eq}/kWh]**	**CED [kWh/kWh]**
[27]-Flash	1.8E-5/1.5E-5	11.4/11.2	5/4.8	3.6/3.5	1.8/1.7	$(0.0062/0.0053)_{f}$
[28]-Flash*	6.1E-4/3.2E-5	647/34				
[35]		5.79/2.25		0.012/0.0047		$(0.014/0.0054)_{nr}$
[24]		9.45/11.6				
[21]		(38-58)/(4.7-6.5)		(0.32-0.45)/(3.6-5.4)E-2		$((0.15\text{-}0.25)/(1.8\text{-}2.8)E\text{-}2)_{nr}$
[23]*		(39-55)/(2.7-4.2)				

3.6.3 Hotspot analysis

3.6.3.1 Flash-CHP plants

Fig. 12 is constructed from the values reported in [28], while no values were reported in [27]. Both studies found that the NCG direct emissions dominate the GW and AC impacts and the construction phase dominate the FWEC and AD impacts. Direct emissions of metals drive the HT impact in [28], while when such emissions are not reported the construction phase plays the prominent role [27]. The construction phase also dominates the CED_f impact in [27]. The drilling of make-up wells causes 15-20% of the AD, HT, FWEC and CED_f in [24], while other maintenance activities cause negligible impact. Also, the machinery replacements and working fluid losses reported in [28] cause less than 0.2% of all impacts.

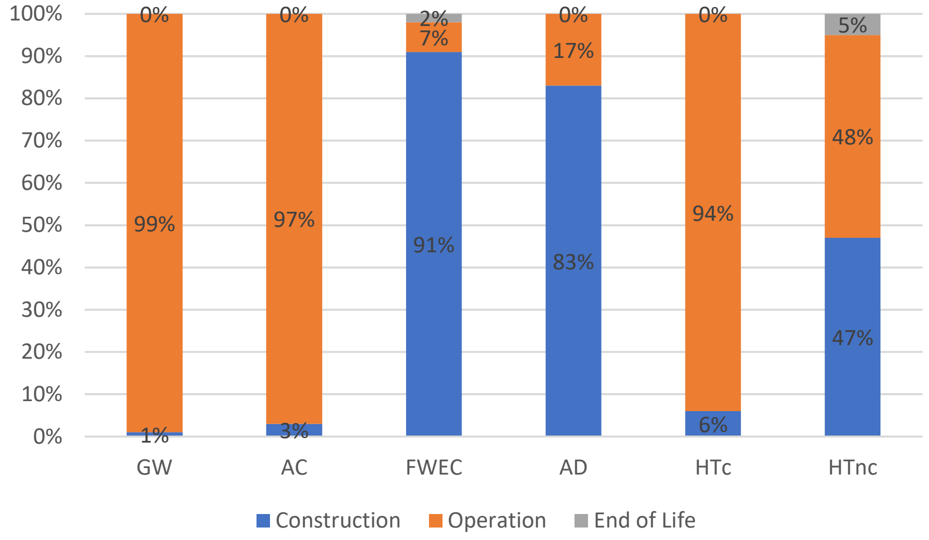

Figure 12: Hotspot analysis of the environmental impacts of CHP-flash plants [28]

3.6.3.2 Binary-CHP plants

Hotspot analysis is performed for three studies [21,23,24]. The wells' development dominates every impact, followed by surface construction activities (Fig. 13a-13c). The operational phase contributes highly to the GW impact in [24] because of the maintenance activities considered (Section 3.4.3). The other studies do not report maintenance activities. Steel and diesel consumption are reported to drive the GW [21,23,24,35] (Fig. 13b), AD, AC, CED [21,35] and AC, HT, FWEC [23] impacts of wells' development.

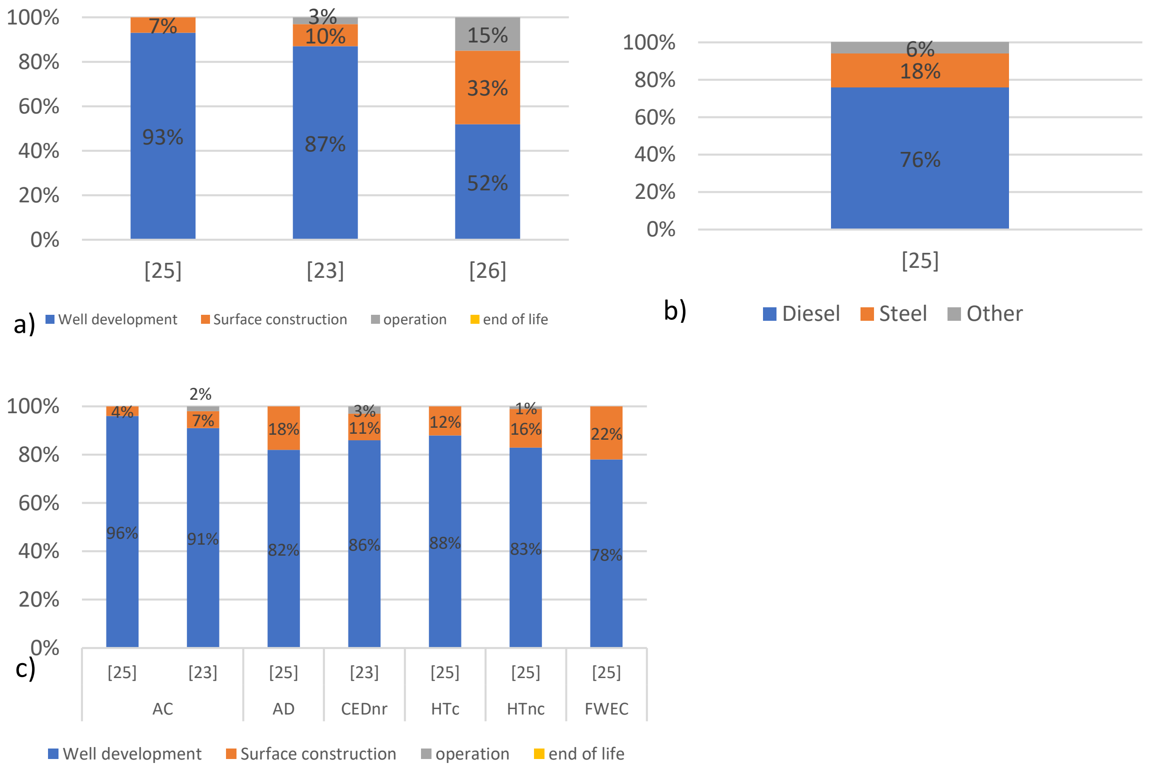

Figure 13: Hotspot analysis of the environmental impacts of binary-CHP plants; (a): lifecycle global warming impact, (b): global warming impact of the development of wells, (c): other impacts.

3.6.4 Results evaluation

3.6.4.1 Flash-CHP plants

The hotspot analyses show that direct emissions dominate the GW impact, while the AD impact is mainly caused from the steel and diesel consumed during the construction phase. High GHG direct emissions (410 g CO_2/kWh_{el}, 12 g CH_4/kWh_{el}) lead to high GW impact (647 g $CO_{2\text{-eq}}$/kWh_{el}) in [28]. A low GW impact (11.4 g $CO_{2\text{-eq}}$/kWh_{el}) is reported in [27], due to low GHG concentration in the geofluid and the presence of a CO_2 capture system. The high energy needs (3898 GJ_{diesel}/$MW_{installed}$), induced by the large number and depth of wells, lead to a high AD impact in [28] . Fewer and shallower wells lead to lower energy needs (1098 GJ_{diesel}/MW) and lower AD impact in [27]. The energy needs are calculated from the provided LCIs.

3.6.4.2 Binary-CHP plants

The hotspot analyses indicate that the impacts are caused mainly during the construction phase. Two studies reported similar GW impact (38-58 g $CO_{2\text{-eq}}$/kWh_{el}), with one reporting longer lifetime and shallower wells [21] and the other reporting higher plant capacity and CF [24]. The drilling material needs in the two studies were similar (95 kg_{steel}/m and 80 kg_{cement}/m [24], 104 kg_{steel}/m and 30 kg_{cement}/m [21]). Relatively low GW impact (9.45 g $CO_{2\text{-eq}}$/kWh_{el}) was reported in [23] because only 45% of the impacts were allocated to the power production. Low GW impact was reported in [35], for low depth (<0.8 km) and relatively high plant capacity. Information regarding the other impacts is limited. However the hotspot analysis shows that they are determined by the same factors as the GW impact, so similar behavior is expected.

3.7 Hybrid systems

Despite growing interest in “hybrid” systems, which combine geothermal energy with other RES, environmental studies in such systems are limited. The environmental performance of geothermal-solar [56,57], geothermal-solar-gas [58] and geothermal-LNG [59] powered plants is assessed through exergoenvironmental/exergy analysis.

An LCA study, investigating a geothermal-solar driven micro-CHP ORC plant, found that the low plant capacity and CF result in much higher GW, AC, and CED impacts than those reported for other RES [60]. These impacts are dominated by the wells’ drilling. Another LCA on a geothermal-biomass heating unit shows that the GW impact is mostly caused by wells’ drilling and the acquisition of the biomass [61]. Still the plant performs better than fossil-fired heating units. Finally, an LCA study recommended using geothermal heat for the suppliance of Lausanne’s heating network to lower the GW and human health impacts [62]. The authors showed that integrating geothermal with woody-biomass systems led to further environmental and economic benefits.

4. Discussion

The results show that there is a wide variability in the environmental impacts reported by the reviewed studies. Fig. 14 presents this variability for the GW impact in box plots. For other environmental impacts, it was not possible to create box plots and analyze the variability in results because of missing information. Note that because we present the results by technology type the sample for each technology is relatively small. Therefore, the results of this section should be interpreted with caution. More data are needed for a more coherent statistical analysis of the impacts. The reported GW impact vary from 31 to 795 g $CO_{2\text{-eq}}$/kWh for dry steam plants with an average value of 375 g $CO_{2\text{-eq}}$/kWh. Similarly, the reported GW impact for flash plants ranges from 3.9 to 680 g $CO_{2\text{-eq}}$/kWh, with an average value of 151 g $CO_{2\text{-eq}}$/kWh. Three outlier points are observed for flash plants. The direct emissions of GHGs (mainly CO_2 and CH_4) lead to the high GW impact in these plants. Note that for one plant the direct emissions were not reported, although the authors stated that they are the main cause of the GW impact [43]. When the outlier point are excluded the GW impact ranges from 3.9 to 245 g $CO_{2\text{-eq}}$/kWh and the average value is 86 g $CO_{2\text{-eq}}$/kWh. Note however that three studies on flash plants excluded direct emissions from the analysis and reported GW values lower than 15 g $CO_{2\text{-eq}}$/kWh. When these studies are excluded, the GW impact ranges from 26 to 245 g $CO_{2\text{-eq}}$/kWh and the average value is 110 g $CO_{2\text{-eq}}$/kWh. The variability range and the average value for the GW impact are larger for dry steam than for flash plants. This is expected because dry steam plants exploit vapor dominated reservoirs which lead to higher direct emissions than when liquid dominated reservoirs are exploited [49].

The GW impact for binary plants varies between 5.7 and 97 g $CO_{2\text{-eq}}$/kWh with an average value of 49 g $CO_{2\text{-eq}}$/kWh. For EGS-binary plants it ranges between 7.5 and 52 g $CO_{2\text{-eq}}$/kWh with an average value of 31.7 g $CO_{2\text{-eq}}$/kWh. Binary plants report zero NCGs emissions, as the geofluid circulates in a closed loop, so the variability ranges and the average values for the GW impact are lower than those reported for dry steam and flash plants. The maximum and the average GW impacts reported are higher for binary than for EGS-binary plants because of one study [39] investigating configurations in which high-GWP working fluids are used and their leakage causes high GW impact.

The GW impact reported for deep heating plants varies from 3.77 to 188 g $CO_{2\text{-eq}}/kWh_{th}$. The average value is 46 g $CO_{2\text{-eq}}/kWh_{th}$. Two studies reported high GW impacts (188 [26] and 59.4 [31] g $CO_{2\text{-eq}}/kWh_{th}$) for plants which are supplied by coal-dominated electricity mixes. Study [26] considered 100% coal-generated electricity to supply the plant and corresponds to the outlier point in Fig. 14. When these studies are excluded the average value is 7.3 g $CO_{2\text{-eq}}/kWh_{th}$ as the plants investigated in the other studies are supplied by less carbon-intensive electricity mixes.

One study on a CHP-flash plant found a high GW impact caused by the direct CO_2 and CH_4 emissions reported [28]. When this study is excluded the average GW impact for power and heat production from CHP plants are 23.3 g $CO_{2\text{-eq}}/kWh_{el}$ and 6.8 g $CO_{2\text{-eq}}/kWh_{th}$ respectively. These are lower than the respective average values technologies producing solely power or heat, indicating that CHP production leads to environmental benefits.

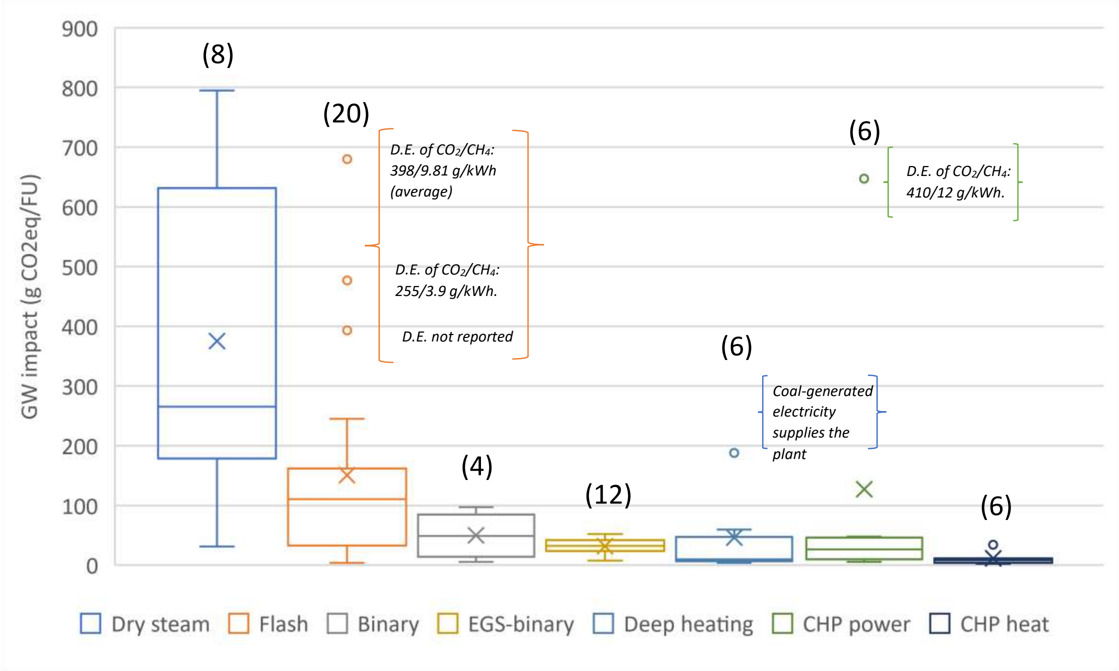

Figure 14: Global warming (GW) impact reported by the studies per technology type. The average value for 2009-2011 for each of the 4 dry steam plants and the 8 flash plants investigated in [43] is presented. The average values for 2002-2009 for each of the 3 dry steam plants and the 1 flash plant investigated in [38] are presented. For study [39] 2 values are presented; the average value among the binary plants using low-GWP working fluids and the average value among the binary plants using high-GWP working fluids. For [17,21,23,25] that report ranges of values, the average value is presented. The number of plants included is noted in parentheses. D.E. refers to direct emissions. The upper and lower borders of the box indicate the 25th and 75th inclusive percentiles, the line inside the box indicates the median value and the X value indicates the mean value. The upper and lower whiskers indicate the maximum and minimum values. Points outside of the whiskers correspond to outlier points.

4.1 Influence of geo-technical parameters on the impacts

In this section we identify the influence of geo-technical parameters on the environmental impacts of geothermal plants and explain their variability. We focus on the GW impact as it is the most frequently assessed impact. For dry steam and flash plants, we consider studies that report the direct emissions as these drive the GW impact (Table 19). For EGS-binary, binary, CHP-binary and flash plants (excluding direct emissions) we consider studies that report the plant capacity, average geofluid temperature and flow and average well depth as these parameters are most frequently reported. The plant CF and lifetime are not considered because they do not vary strongly among the studies. Also, information regarding the rock formations and the geofluid composition and specific heat capacity, which can also influence the impacts, is often missing in the reviewed studies and therefore could not be included in this analysis.

Table 19: Impacts versus geo-technical parameters reported in the studies. Emissions of CO_{2-eq}, H_2S, SO_2 and NH_3 in g/kWh. GW and AC impacts in g CO_{2-eq} or g SO_{2-eq}, respectively, per functional unit. Capacity (MW), Temperature (°C), Flow (kg/s), Depth (km). All values refer to average values reported in the respective studies.CO_{2-eq} emissions are calculated from the CO_2 and CH_4 direct emissions using a factor of 28 for the CH_4 [63]. **SO_2 emissions. ***Excluding direct emissions.*

Plant type	Study	CO_{2-eq} emissions*	GW impact	H_2S/SO_2 emissions	AC impact	NH_3 emissions
Dry steam	**[16]**	181.3	248	5.79	3.37	1.92
	[38]	675.2	682	6.79	3.46	2.96
Flash	**[18]**	41.6	47	0.16	0.40	0.06
	[19]	98.7	118	1.02**	1.95	0
	[37]	336.9	477	0.92	2.27	0.075
	[38]	604.0	702	1.53	17.1	14.1
CHP-flash	**[28]**	628.9	647	N.A.	N.A.	N.A.

Plant type	Study	GW impact	Capacity	Temperature	Flow	Depth
Flash* **	**[20]**	11.8	0.225	91	64	0.8
	[20]	3.88	16	160	125	0.3
Binary	**[20]**	80.5	0.15	110	33	3.2
	[39]	65	5	141	120	3.7
	[33]	5.7	10	240	*N.A.*	2
EGS-binary	**[21]**	52	0.91	125	69.4	3.8
	[23]	46.7	0.67	175	21	5
	[15]	45.6	2.9	150	147	5
	[22]	36.7	1.61	165	40	4
	[24]	36	2.86	150	82.5	6.9
	[15]	28.9	5.5	175	147	5
	[24]	24.7	3.7	170	82.5	5.7
	[20]	12.7	2.8	236	28	3.7
	[15]	7.55	14.6	240	147	6
CHP-binary	**[35]**	5.79	2.9	150	70	0.6
	[21]	48	0.67	125	69.4	3.8
	[23]	47	0.67	175	21	4

In Fig. 15 we plot a regression line, showing that there is a positive relationship between the CO_2 and CH_4 direct emissions and the GW impact of dry steam and flash plants reported in the studies. The R^2 value is high (0.97), however the sample size is small and thus this result should be interpreted with caution. A similar relationship is indicated between the AC impact and the H_2S/SO_2 direct emissions in Fig. 16. However, when study [38] is included the R^2 value reduces from 0.76 to 0.0019. This is because this study finds a large AC impact (17.1 g SO_{2-eq}/kWh), driven by NH_3 emissions (14.1 g/kWh). This highlights the sensitivity of these results to the size of the sample. More studies reporting the direct emissions are needed before making general conclusions. The results evaluation (Sections 3.1.4 and 3.2.4) indicate a similar relationship between the HT/FWEC impacts and the direct emissions of metals (e.g., Hg, Pb, As), however the number of studies reporting such data is limited.

The NCGs emitted are determined by the geofluid's composition, which is not often reported in LCA studies. The geofluid's composition is highly site-specific and depends on the rock formations, the depth of the reservoir and the temperature and phase of the geofluid. Thus, these parameters drive the impacts of flash and dry steam plants. For example, a high HT impact is reported in [38], in which the geofluid is extracted from an area with high Hg concentration, while low HT impact is reported in [18], where no emissions of metals are reported. However, the NCGs emitted are also influenced by design parameters such as the presence of abatement systems, the re-injection of the geofluid or the use of binary technology.

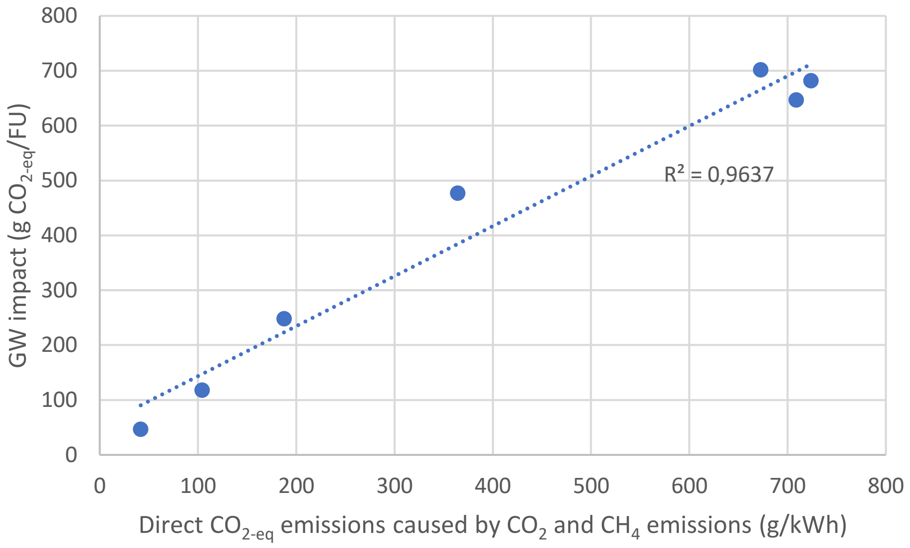

Figure 15: Global warming (GW) impact versus direct emissions of CO_2 and CH_4 reported in the studies. For translating CH_4 emissions to $CO_{2\text{-eq}}$ a factor of 28 is used [63]. The functional unit (FU) refers to 1 kWh and varies across the studies depending on the methodological choices.

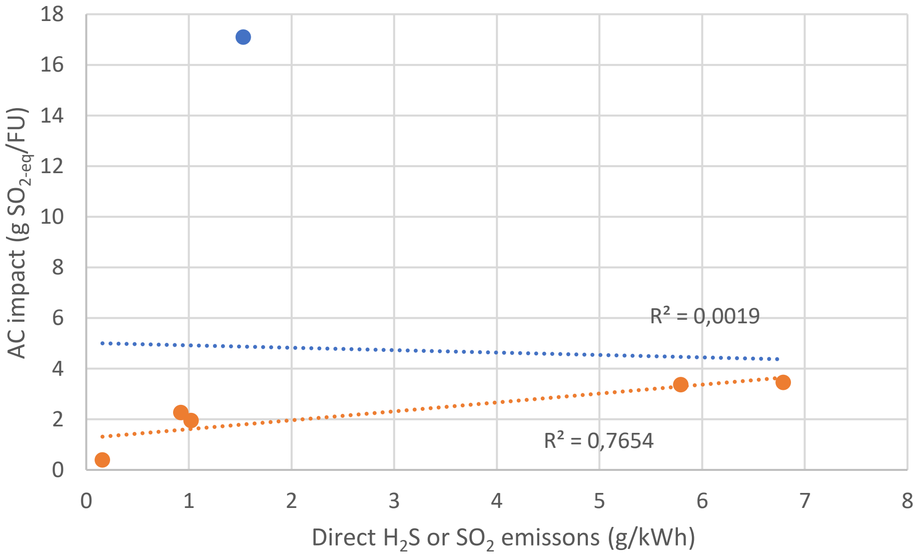

Figure 16: Acidification (AC) impact versus direct emissions of H_2S and SO_2 reported in the studies. The functional unit (FU) refers to 1 kWh and varies across the studies depending on the methodological choices.

Fig. 17a suggests that the exploitation of geofluids with higher temperature leads to lower GW impact per kWh. This is expected, as higher temperature leads to higher plant capacity and higher energy output. However, the plant capacity is also influenced by other parameters (such as the production flow, the geofluid's specific heat capacity and the efficiencies of the power production equipment). Fig. 17a, although indicates that plants with high capacity report relatively low GW impact and that for similar temperatures higher capacity leads to lower GW impact. The GW impact is also affected by other parameters further explaining the low R^2 value (0.26) value of the regression line. For example, the working fluid losses considered for two binary plants (points in the upper left part of Fig. 17a) lead to large GW impacts. Also, a flash and a CHP-binary plant (points in the lower left part of Fig. 17a) use relatively shallow wells (0.3 and 0.4-0.7 km) and this leads to low GW impact in relation to the capacity. Fig. 17b shows no relationship between the average well depth and the GW impact or between the well depth and the plant capacity. The, per meter drilled, energy and material needs for the drilling and casing of the wells increase with the well depth [15]. However, extracting geofluid from deeper wells, comes with increased geofluid temperature. The increased energy output can compensate for the increased drilling impacts depending on the geothermal gradient at the specific location and depth and the rock formations present. Furthermore, no relationship is shown between the production flow and the GW impact in Fig. 17c, albeit the plant capacity is determined by the production flow. This is because the production flow is a design parameter which can be altered through the production and re-injection pumps. For example, study [15] investigated three scenarios with a constant flow value and variable temperature and total length drilled values. Also, study [24] considers constant flow for the two case studies investigated. However, Fig. 17c shows that for similar production flow plants with higher capacity report lower GW impact. Note that the sample size used for this analysis is limited and the results should be interpreted with caution. More LCA studies should be performed for more coherent conclusions to be extracted.

Similar results are presented for the AC impact in Fig. A2-A5. For the HT, CED, AD and FWEC impacts the information is limited. However, the hotspot analyses show that in binary, EGS-binary and flash plants (excluding direct emissions) they are determined by the same factors as the GW impact and thus similar behavior is expected. Information about the WC impact is much more limited and conclusions could not be extracted. A previous review study has indicated that the water consumption for geothermal power plants is lower than fossil-fired plants [3].

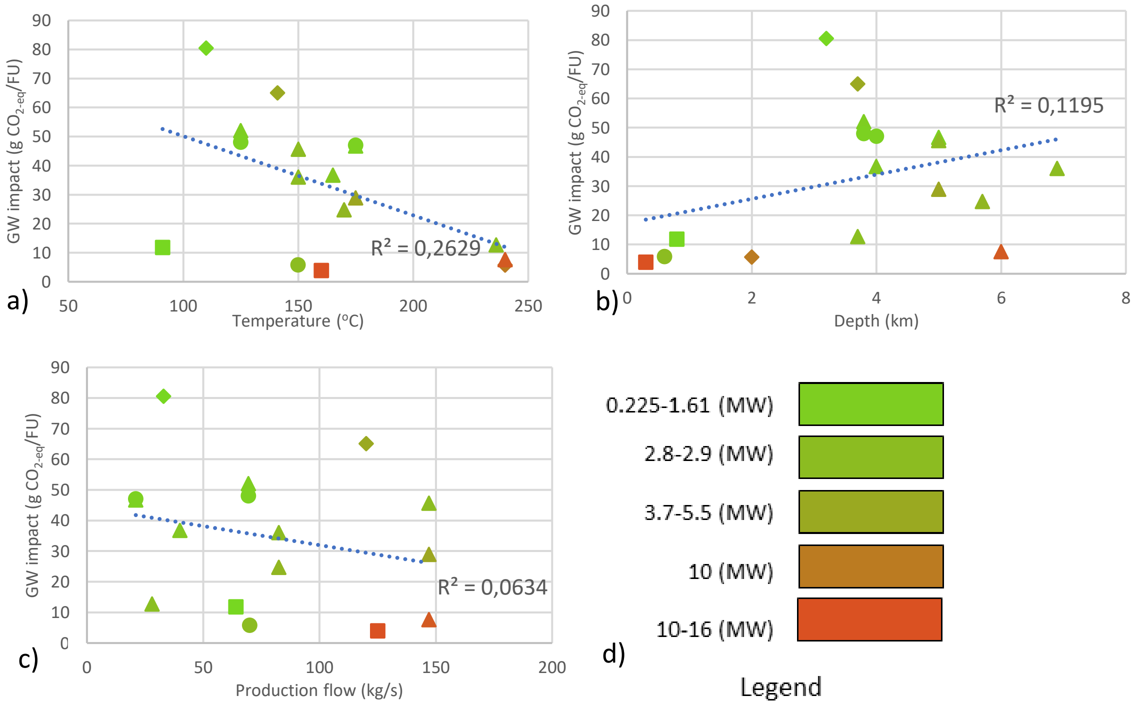

Figure 17: Global warming (GW) impact in relation to: (a) average geofluid temperature, (b) average well depth, (c) average production flow. Green color denotes low capacity, while red color denotes high capacity (see (d)-Legend). Triangle denotes EGS-binary plants, diamond denotes binary plants, square denotes flash plants (excluding direct emissions), circle denotes CHP-binary plants. The average values reported in the studies are used. The functional unit (FU) refers to 1 kWh and varies across the studies depending on the methodological choices.

For deep geothermal heating systems, the information regarding geo-technical parameters is often missing (Table 15). Impacts dominated by the construction phase are expected to have similar behavior with the impacts of binary/EGS-binary plants. However, the impacts of heating plants are also influenced by their electricity needs as they do not produce power for self-consumption. Thus, the pumping needs of the plant (determined by the reservoir permeability and depth and the production flow) and the electricity mix supplying the plant also drive the impacts. Supplying the plant with fossil-dependent electricity in [26,31] leads to high GW impact (188 and 59.4 g $CO_{2\text{-eq}}$/kWh). Studies reporting more RES-dependent electricity mixes [24,25,29,30] report also lower GW impact (average 7.3 g $CO_{2\text{-eq}}$/kWh). Furthermore, the construction of the distribution network can cause high impacts, as in [24,29], depending on its length, although this activity is frequently excluded from the boundaries of the analysis.

The above indicate that the environmental impacts of geothermal energy plants are not dependent on a limited number of parameters. Instead, they are determined by the combination of various site-specific geological (such as temperature, flow, depth, rock formations), design (such as capacity, capacity factor, energy conversion technology used, abatement systems, working fluid used, pumping needs) and construction parameters (such as drilling and casing techniques used for the development of wells). The above analysis shows some evidence on the effect of specific parameters in the impacts. However, the sample size is small and the results should be interpreted with caution. The effect of more parameters needs to be addressed. Parameters such as the geofluid composition, specific heat capacity and pressure, the plant energetic efficiency, type of working fluid and its leakage as well as the reservoir rock formations and permeability are often not reported and no analysis could be made. More LCAs, reporting these parameters, are needed to acquire a transparent picture of the cause-effects relationships between the impacts and the geo-technical parameters.

Moreover, the reviewed studies follow different methodological choices, a fact that impedes the extraction of conclusions. The plant lifetime reported varies from 20 to 40 years, with most studies using 30 years. Also, the exploration and EoL activities considered vary among the studies. The exploration and EoL activities are shown to cause a low share of the environmental burden. However, another study shows that only the subsurface decommissioning can cause up to 20% of some impact categories [51]. Additionally, many of the reviewed studies calculate impact categories such as the AC and HT_c using different LCIA methods and their results could not be used in this study. Widening the application of harmonized guidelines on geothermal LCA (such as in [13]) could facilitate future reviews. Also, the number of LCAs on deep geothermal heating systems is very limited.

4.2 Research agenda

We propose the following research agenda to advance research on the environmental performance of geothermal energy developments.

All reviewed LCA studies follow a static approach. We show that a significant portion of geothermal energy's environmental impacts is caused during the operational phase. Thus, LCA studies should also adopt a dynamic approach. The expected, variations in time of the most important processes should be introduced in the LCI by splitting the LCI up in different time-steps to account for these variations. For example, the NCGs direct emissions are expected to vary with time [38,43,49] and considering this dynamic could lead to more accurate impact estimations. Also, the electricity mix and the drilling and material production technologies are expected to vary in time. Also, the timing of the emissions should be considered during the LCIA phase [64]. Previous dynamic LCA studies have shown that the results can be much different than when static approaches are followed [65,66].

For a comprehensive sustainability assessment of geothermal energy, environmental LCA should be complemented with social and economic assessments. There is a lack of life cycle costing (LCC) studies on geothermal energy compared to other RES. LCC should be performed to identify the major cost drivers of geothermal development and suggest solutions for cost reduction. Also, social LCA should be employed to identify the social impacts and benefits and facilitate the social acceptance of geothermal energy solutions.

Future LCA studies should deal with environmental impacts other than the GW, such as induced seismicity and the land and water use. Information regarding the, crucial, WC impact is scarce. Also, more research is required about the toxicity-related and energy consumption impacts for which the reported information is limited.

Moreover, none of the studies distinguished between anthropogenic and natural NCG emissions, except for a scenario in [37], which considered 40% of the emissions to be natural. Natural emissions refer those that would occur due to natural leakage and some researchers have suggested that they should be deducted from the plant's emissions [67,68]. The effect of energy production on natural emissions can vary for different sites and different time periods. For the Ohaaki plant, energy production is expected to cause an increase on the CO_2 emissions compared to the natural state, for 100 years of analysis [68]. For 300 years however, the CO_2 emissions compared to the natural state are lower, as the geofluid's exploitation causes its depletion on NCGs. Also, studies indicating that energy production either increase or decrease the emissions compared to the natural state have been reported [5]. Data regarding the natural emissions occurring prior to the development of a geothermal plant are usually not available. Also, the recommendations on whether to consider or not natural emissions as caused emissions from a geothermal plant vary between different countries [51] and therefore they should be included in future LCAs in the context of sensitivity or scenario analysis.

5. Conclusions

This study reviewed 30 LCA studies on deep geothermal energy extraction. We explained the variability in the reported results by investigating the differences in the site-specific geological and design characteristics. The major environmental factors are also identified. Our findings suggest that the environmental impacts of geothermal energy extraction are driven by various highly site-specific geological conditions such as the reservoir depth, the geofluid's temperature and composition and the rock formations. Also, design parameters such as the energy conversion technology, the production flow, and the plant capacity, CF and lifetime influence the environmental impacts. Direct NCGs emissions, dominate the environmental burden of dry steam and flash plants. Construction activities such as the development of the wells play a prominent role on the impacts of binary plants and heating plants. However, the environmental performance of the latter is also dependent on the plant's pumping needs and on the electricity mix supplying the plant. Most of the studies reviewed, assessed the GW impact. Information regarding the WC and the other impacts is limited. Despite the increasing interest on geothermal energy many aspects of its environmental impacts remain underexplored. The influence of more geo-technical parameters on the impacts needs to be assessed in order to further identify the factors driving the environmental impacts of geothermal energy extraction. Also, although deep geothermal heating has been shown to cause very low GW impact per kWh_{th} produced, we only found a few LCAs that investigated such plants, so future research should also focus on this aspect of geothermal energy exploitation. Additionally, a time component is usually not considered in geothermal LCAs, although the processes causing the majority of the environmental burden are expected to vary over time.

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Appendix.

Table A1: LCA methodological choices. The functional unit (FU) of the studies vary regarding to the boundaries of the analysis (denotes that it is delivered to the consumer). Hyp. denotes that the plant is hypothetical. For CHP plants the allocation method followed is based on the exergy content. CTGR: Cradle to grave, CTGT: Cradle to gate, GTG: Gate to gate.*

Study	Scope	Location	FU	Impact ID	LCIA method	Database	Software	Plant
Dry steam								
[43]	CTGT	USA	kWh	1	N.A.	GREET	N.A	Real
[38]	GTG	Italy	MWh	1-3	CML-2002	N.A.	SimaPro	Real
[16]	CTGR	Italy	kWh	1-3,5,7	CML-2001,CED	ecoinvent	N.A.	Real
Flash								
[42]	CTGR	Turkey	kWh	1-5,7	CML-2001	Ecoinvent,ESU	GaBi-v.6	Hyp.
[38]	GTG	Italy	MWh	1-3	CML-2002	N.A.	SimaPro	Real
[43]	CTGT	USA	kWh	1	N.A.	GREET	N.A	Real
[37]	CTGR	Italy	kWh	1-4,8	ReCiPe-2016,ILCD-2011	Ecoinvent	OpenLCA-1.10	Real
[40]	CTGT	Japan	kWh	1	N.A.	N.A.	N.A.	Hyp.
[17]	CTGT	Iceland	kWh	1,6	CML-2000,CED	Ecoinvent	SimaPro-7	Real
[18]	CTGR	Guadeloupe	kWh	1,3,5,6	ILCD-2011	Ecoinvent-2.2	N.A.	Real
[19]	CTGR	New Zealand	kWh	1-4,6	N.A.	Ecoinvent-2.2,EXIOBASE	THEMIS	Real
[41]	CTGR	New Zealand	kWh	1,6	N.A.	N.A.	SimaPro-7	Real
[34]	CTGT	USA	MWh*	1	IPCC-2007	N.A.	N.A.	Hyp.
[33]	CTGR	USA	kWh	1	N.A.	GREET	N.A	Hyp.
[32]	CTGT	USA	kWh	8	N.A.	N.A.	N.A.	Hyp.
[20]	CTGR	China	kWh	1,2,7	IPCC-2007,CML-2002	N.A.	eBalance	Hyp.
Binary								
[39]	CTGR	Germany	kWh	1,2,6,7	N.A.	Ecoinvent,PROBAS	N.A.	Hyp.
[33]	CTGR	USA	kWh	1	N.A.	GREET	N.A	Hyp.
[20]	CTGR	China	kWh	1,2,7	IPCC-2007,CML-2002	N.A.	eBalance	Hyp.
EGS-binary								
[15]	CTGR	Switzerland	kWh	1-4,8	ReCiPe	Ecoinvent	SimaPro-7.3.3	Hyp.
[21]	CTGR	Europe	kWh	1,2,6,7	N.A.	Ecoinvent	N.A.	Hyp.
[22]	CTGR	France	kWh	1,6	IMPACT-2002+	Ecoinvent-2.2	N.A.	Hyp
[23]	CTGR	UK	kWh	1-5,8	ILCD	Ecoinvent-3.4	Gabi-v.8	Hyp.
[24]	CTGR	France	kWh	1	ILCD-2011	Ecoinvent,USLCI,Agri-BALYSE	OpenLCA-1.6.3	Real
[33]	CTGR	USA	kWh	1	N.A.	GREET	N.A	Hyp.
[32]	CTGT	USA	kWh	8	N.A.	N.A.	N.A.	Hyp.
[36]	CTGR	Europe	kWh	1	ReCiPe,IMPACT-2002	Ecoinvent 2.2	SimaPro-7.3.3	Real
[44]	CTGR	Germany	kWh	1,2,6,7	N.A.	IFEU	Umberto	Hyp.
[20]	CTGR	China	kWh	1,2,7	IPCC-2007,CML-2002	N.A.	eBalance	Hyp.
Deep heating								
[29]	CTGT	Iceland	kWh*	1-7	CML-2000,CED	Ecoinvent	SimaPro	Real
[25]	CTGR	UK	MWh*	1	N.A.	N.A.	N.A.	Hyp.
[24]	CTGR	France	kWh	1	ILCD-2011	Ecoinvent,USLCI,Agri-BALYSE	OpenLCA-1.6.3	Real
[26]	CTGT	China	GJ	1,2,7,8	IPCC,ReCiPe,IMPACTWorld+	Ecoinvent,CPLCID	N.A.	Hyp.
[31]	CTGR	China	kWh	1	N.A.	N.A.	N.A.	Hyp.
[30]	CTGR	France	kWh	1,5,7	Environmental footprint v.2	Environmental footprint v.2	OpenLCA V1.10.3	Real
CHP								
[27]	CTGT	Iceland	kWh$_{el/th}$	1-7	CML,CED	Ecoinvent	SimaPro-8	Real
[28]	CTGR	Italy	kWh$_{el}$	1-5	ILCD-2011	Ecoinvent-3.5	OpenLCA-1.10	Real
[35]	CTGT	Europe	MWh$_{el/th}$	1,2,5,7	CML,CED	Ecoinvent	SimaPro-7	Hyp.
[23]	CTGR	UK	kWh$_{el}$	1-5,8	ILCD	Ecoinvent-3.4	Gabi-v.8	Hyp.
[21]	CTGR	Europe	kWh$_{el}$/MJ$_{th}$	1,2,6,7	N.A.	Ecoinvent	N.A.	Hyp.
[24]	CTGR	France	kWh$_{el/th}$	1	ILCD-2011	Ecoinvent,USLCI,Agri-BALYSE	OpenLCA-1.6.3	Real

Table A2: Goal of the reviewed studies, as mentioned in the studies.

Study	Goal
[43]	develop a life cycle GHG emissions rate profile for geothermal power production in California.
[38]	evaluate the environmental impact of selected geothermal power plants
[16]	present and discuss the environmental performance of a geothermal power plant located in the Tuscany region
[42]	estimate the life cycle environmental impacts of electricity generation from the renewable power systems in Turkey.
[37]	compare the environmental performances of three power plants based respectively on geothermal, solar, and wind energy
[40]	understand the characteristics of the power generation systems from the perspective of global warming.
[17]	analyze the primary energy efficiency and the CO2 emissions for the electricity production at Helisheidi geothermal power plant
[18]	Perform the LCA of in high temperature geothermal system in Guadeloupe. Compare technological alternatives to present situation to investigate potential reduction of environmental impacts
[19]	conduct a hybrid LCA for the Wairakei Geothermal Project by using two inventories: mass requirements and monetary capital.
[41]	compare the differences in the life cycle sustainability of four renewable energy technologies in a New Zealand-specific context,
[34]	N.A.
[33]	present LCA results derived from our modeling of four geothermal plant types: two EGSs, a hydrothermal binary, and a hydrothermal flash.
[32]	examine water consumption by geothermal projects at a regional scale
[20]	present LCA focusing on research of environmental impacts for four different of typical geothermal power generation systems located in discrete regions of China
[39]	Evaluation of the environmental impact of geothermal ORC power plants
[15]	quantification of environmental burdens during the complete life cycle of deep geothermal systems per unit of electricity (and heat) generated under various conditions in Switzerland.
[21]	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.
[22]	evaluate the environmental performances of EGS
[23]	quantifies the life-cycle environmental impacts of the electricity expected to be generated by a geothermal plant in the UK
[24]	estimate the climate change impact of electricity and heat production from an existing geothermal plant, Rittershoffen, and from the future geothermal plant in Illkirch.
[36]	quantify and compare impacts on human health including effects of climate change due to power generation with centralized future generating
[44]	investigate the environmental performance of renewable energy systems particularly in view of future developments
[29]	create a life cycle inventory (LCI) database and perform a cradle-to-gate life cycle assessment (LCA) on Stykkishólmur's geothermal district heating system
[25]	estimate the whole life cycle climate impact of direct heat production from low-enthalpy deep geothermal projects
[26]	quantify the environmental impact of geothermal heating in China, identify the key factors and potential measures for the environmental improvement, and examine the cleanliness of geothermal heating.
[27]	investigate the environmental impacts of a geothermal power plant that uses flashing technology to produce energy from a high-temperature geothermal resource.
[28]	assess the potential environmental impacts that are associated with the production of electricity from the geothermal power plants of Bagnore 3 and Bagnore 4
[35]	Determine the lifecycle environmental and energy performance of power generation in a geothermal binary-cycle power plant using high-enthalpy resources and of heat generation in a closed loop geothermal heat pump system using low enthalpy resources.
[31]	comprehensively evaluate the coaxial borehole heat exchanger and the horizontally-butted borehole heat exchanger from the life cycle, including economy, thermal efficiency and environmental impact
[30]	assess the environmental impacts related to heat production from the Rittershoffen geothermal heat plant

Table A3: Direct emissions, in g/kWh, of the three dry steam plants investigated in [38]. *Minimum, maximum and average values are provided for each plant, while the median value is calculated for all plants. The data refers to annual emissions monitored from year 2002 to 2009.*

	[38]									
	Plant 1			Plant 2			Plant 3			
Substance	Average	Min	Max	Average	Min	Max	Average	Min	Max	Median
CO_2	465	413	500	529	473	585	677	554	779	529
CH_4	5.45	2.31	8.84	8.2	4.21	12.2	6.96	5.03	7.91	6.96
H_2S	3.49	0.263	10.7	8.01	6.79	9.24	3.05	0.0397	11.4	6.79
NH_3	2.74	0.645	7.83	5.11	2.96	7.25	1.55	0.0859	5.83	2.96
As	6.6E-06	1.4E-06	1.6E-05	4.5E-05	4.6E-06	8.5E-05	1.9E-05	3.1E-06	3.5E-05	1.6E-05
Hg	1.2E-06	1.9E-09	3.6E-06	1.2E-06	4.1E-07	1.9E-06	0.000217	1.4E-08	0.00053	1.2E-06
H_3BO_3	0.0186	0.00226	0.0507	0.023	0.0175	0.0285	0.0279	0.0118	0.036	0.023
As compounds	2.4E-07	1.9E-07	2.72E-07	9.7E-07	9.7E-07	9.7E-07	3.62E-07	3.62E-07	3.62E-07	3.62E-07
Sb compounds	8E-06	1.68E-08	1.24E-05	7.88E-05	7.88E-05	7.88E-05	1.78E-05	1.78E-05	1.78E-05	1.78E-05
Se	2.6E-05	3.53E-08	5.98E-05	4.97E-06	4.97E-06	4.97E-06	8.59E-05	8.59E-05	8.59E-05	2.59E-05
Cd	0.00069	0.000141	0.00182	0.00223	0.00105	0.00342	0.0012	0.000663	0.00175	0.0012
Cr	3.1E-09	1.59E-10	9.24E-09	9.3E-09	1.64E-09	1.7E-08	1.17E-08	1.04E-08	1.3E-08	9.3E-09
Mn	4E-06	9.73E-09	0.000012	4.06E-07	3.07E-08	4.85E-07	4.86E-07	5.21E-08	9.2E-07	4.85E-07
Ni	1.8E-07	1.96E-08	4.57E-07	3.04E-07	8.77E-08	5.21E-07	1.63E-07	2.6E-08	3.01E-07	1.77E-07
Pb	1.7E-06	2.16E-08	4.95E-06	8.29E-07	6.06E-07	1.05E-06	3.61E-07	3.44E-07	3.79E-07	6.06E-07
Cu	1.5E-07	1.95E-09	4.57E-07	5.17E-08	1.58E-08	8.77E-08	2.37E-08	1.3E-08	3.44E-08	3.44E-08
V	1.8E-07	1.52E-08	4.57E-08	1.35E-07	8.77E-08	1.82E-07	3.94E-07	5.21E-08	7.36E-07	1.35E-07
CO	0.0364	0.00685	0.0535	0.0243	0.0176	0.031	0.0638	0.052	0.0725	0.0364

Table A4: Direct emissions, in g/kWh, of the flash plant investigated in [38]. Minimum, maximum and average values are provided for each plant, while the median value is calculated for all plants. The data refers to annual emissions monitored from year 2002 to 2009.

	[38]			
Substance	Average	Min	Max	Median
CO_2	1.53	0.99	2.26	1.53
CH_4	1.20E-06	5.73E-07	2.00E-06	1.2E-06
H_2S	1.03E-06	7.81E-08	2.93E-06	1.03E-06
NH_3	398	245	656	398
As	14.1	4.48	28.9	14.1
Hg	2.65E-05	1.74E-05	4.64E-05	2.65E-05
H_3BO_3	1.02E-05	1.1E-08	2.05E-05	1.02E-05
As compounds	1.75E-05	4.87E-08	2.98E-05	1.75E-05
Sb compounds	1.62E-04	6.19E-05	0.000249	0.000162
Se	4.35E-08	1.49E-09	1.08E-07	4.35E-08
Cd	2.83E-07	3.65E-08	5.15E-07	2.83E-07
Cr	3.36E-07	1.79E-07	5.15E-07	3.36E-07
Mn	6.88E-07	5.08E-07	1.04E-06	6.88E-07
Ni	2.6E-07	5.64E-08	5.15E-07	2.6E-07
Pb	3.67E-07	6.67E-08	7.73E-07	3.67E-07
Cu	1.89E-08	2.08E-08	5.15E-07	2.08E-08
V	0.00857	0.00269	0.0149	0.00857
CO	9.81	5.77	17	9.81

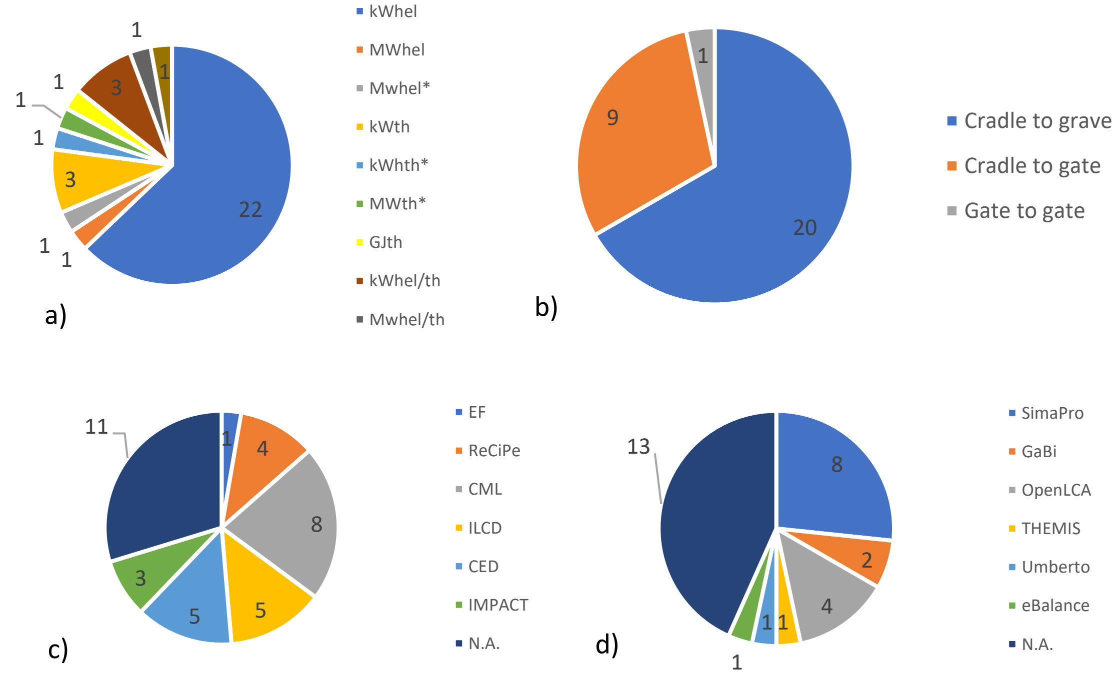

Figure A1: Number of studies adopting methodological choices. a) Functional units. The number is higher than 30 because of the studies that investigate more than one types of plants (e.g., binary power and deep heating plants). b) Scope. Cradle to grave refers to studies that include at least one activity taking place after the plant's closure. c) Impact assessment method used (N.A. refers to when this information is not available). The number is higher than 30 because of the studies using more than one impact assessment method, d) Software used (N.A. refers to when this information is not available).

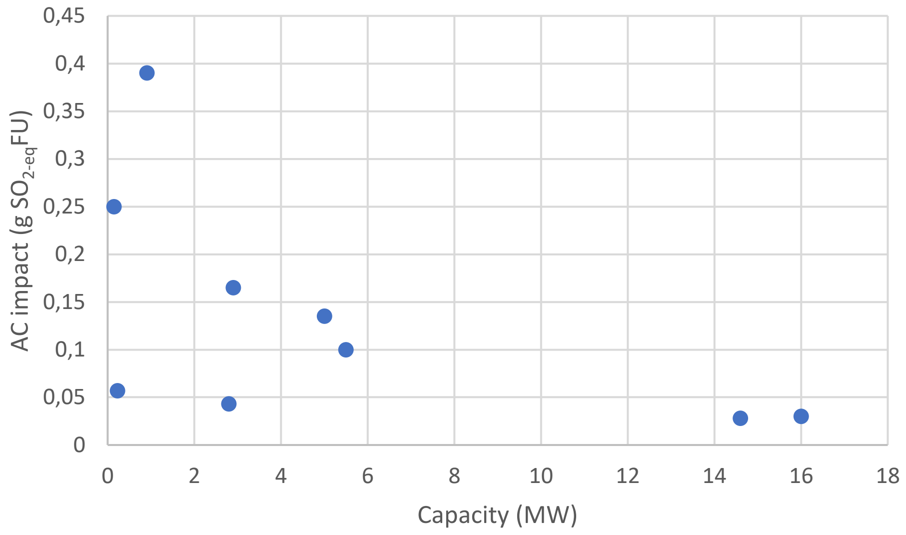

Figure A2: Acidification (AC) impact versus plant capacity, for the reviewed studies. The functional unit (FU) refers to 1 kWh and varies across the studies depending on the methodological choices.

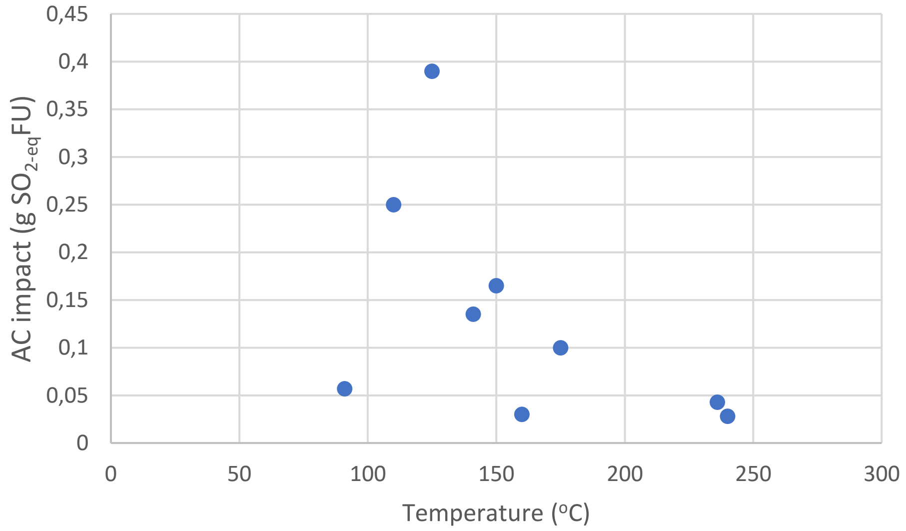

Figure A3: Acidification (AC) impact versus geofluid average temperature, for the reviewed studies. The functional unit (FU) refers to 1 kWh and varies across the studies depending on the methodological choices.

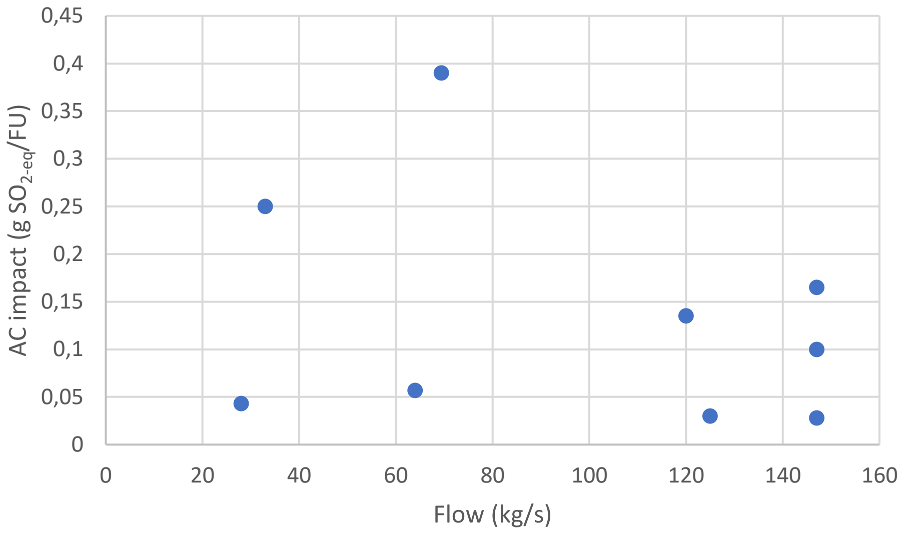

Figure A4: Acidification (AC) impact versus average production flow, for the reviewed studies. The functional unit (FU) refers to 1 kWh and varies across the studies depending on the methodological choices.

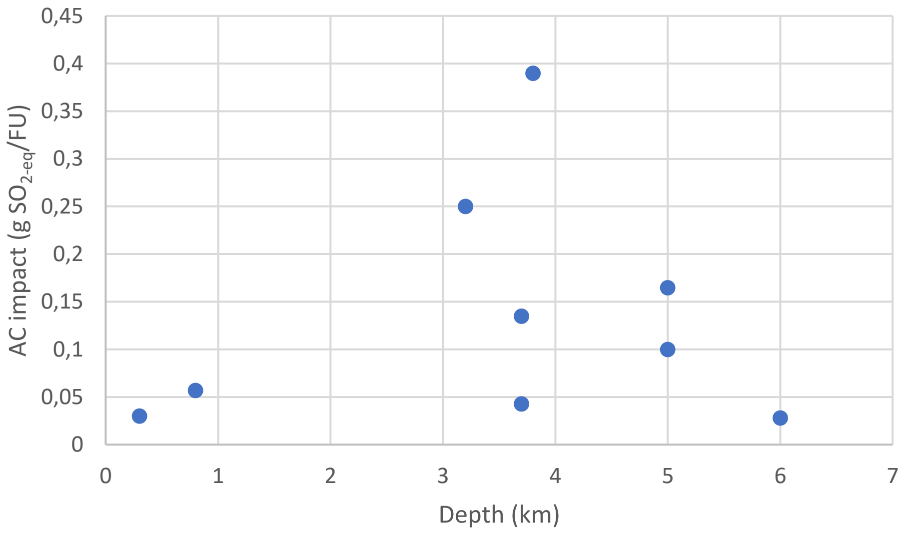

Figure A5: Acidification (AC) impact versus average well depth, for the reviewed studies. The functional unit (FU) refers to 1 kWh and varies across the studies depending on the methodological choices.

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