Review of Life Cycle Assessments of Geothermal Heating Systems

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ABSTRACT

The State of Geneva in Switzerland is determined to increase the share of renewable energy in its heating and cooling mix. Geothermal energy from shallow and medium depths (up to 3000 m) is identified as one of the key renewable sources. As compared to other renewable energy sources, there are relatively few studies on the environmental impacts of geothermal energy. This paper provides a systematic review of 28 geothermal heating and cooling system designs from 25 Life Cycle Analysis (LCA) publications. This review discusses (1) the scope of the existing LCA studies; (2) technologies assessed; (3) methodologies and reported environmental impacts; (4) different factors that give rise to the uncertainty and variability of the result; (5) limitations and challenges faced during the studies; and (6) gaps in the literature and future research needs. The findings show that the systems with borehole heat exchangers and heat pumps were analyzed the most. These geothermal systems did not necessarily perform better environmentally than oil boilers. Sensitivity analyses showed that electricity mix and coefficient of performance of the heat pumps were the key influencing factors. Studies on geothermal systems involving groundwater extraction at shallow and medium depths were rarely carried out despite their wide deployment in Europe. In the few existing studies, such systems had better environmental performance than small-scale oil boilers. Additionally, in general, uncertainty and variability were not analyzed.

1. INTRODUCTION

The building sector plays an important role in Switzerland's climate policy as it is the source of approximately a quarter of the country's CO_2 emissions (FOEN, 2018). Heating and cooling supply in buildings from oil and gas boilers (Narula et al., 2019) is one of the primary sources of these emissions. Therefore, Switzerland has promoted investment in renewable energy for buildings (FOEN, 2018). There has been also increasing attention to geothermal energy throughout the country as renewable source.

In Geneva, where fossil fuel also dominates the heating sector (Quiquerez et al., 2017), geothermal energy has been identified as one of the prominent sources of renewable energy. A study in 2011 showed that geothermal energy could cover 75% of the heating demand in Geneva in 2050 (Groupe de travail PGG, 2011). GEothermie 2020 program, a collaboration between the State of Geneva and a utility company Services industriels de Genève (SIG), responds to this finding by carrying out projects to comprehend Geneva's subsurface characteristics better and to develop new geothermal projects.

The GEothermie 2020 program also considers sustainability management aspects as part of their comprehensive strategy towards exploiting the geothermal energy potential, including three pillars of sustainability: environmental (Life Cycle Assessment / LCA), economic (Life Cycle Costing / LCC) and social (Social Life Cycle Assessment / SLCA) (Finkbeiner et al., 2010). LCA is an increasingly recognized methodology because it permits a holistic evaluation of the environmental impacts of the whole value chain of a product.

The purpose of this conference paper is to review existing LCA studies that evaluate the environmental performances of geothermal heating and cooling systems. This review discusses (1) the scope of the existing LCA studies; (2) technologies assessed; (3) methodologies and reported environmental impacts ; (4) different factors that give rise to the uncertainty and variability of the result; (5) limitations and challenges faced during the studies; and (6) gaps in the literature and future research needs.

2. METHODOLOGY

The methodology used to perform this review is divided into three main steps as summarized in Figure 1: analysis of the existing LCA reviews, analysis of the existing LCA publications, and then a detailed analysis of the environmental impacts in these publications. During the first step, we found and analyzed existing reviews on LCA studies that involve geothermal use for heating and cooling applications. In the second step, a search was carried out to obtain all available LCA publications of such systems in two scientific repositories: ISI Web of Knowledge and Scopus. The entered keywords for the search were divided into three sets. Set 1 included *geothermal, hydrothermal, aquifer, geo, medium,* and *shallow*. Set 2 included *LCA, life cycle assessment, environment,* and *life cycle.* Set 3 included *heating* and/or *cooling, heat network, district heating, low-enthalpy, heat pump, GSHP, heat exchanger,* and *HVAC.* The search aimed to find all articles written in English containing at least one keyword from each set, with no limits to the years of publication. As a result, 353 publications were identified. These publications were then screened based on the relevance of the titles or abstracts. The studies concerning horizontal exchangers and geothermal piles were not considered. At this point, 36 system designs from 28 publications were selected. Afterwards, we filtered out non-LCA studies, leaving 28 system designs from 25 publications.

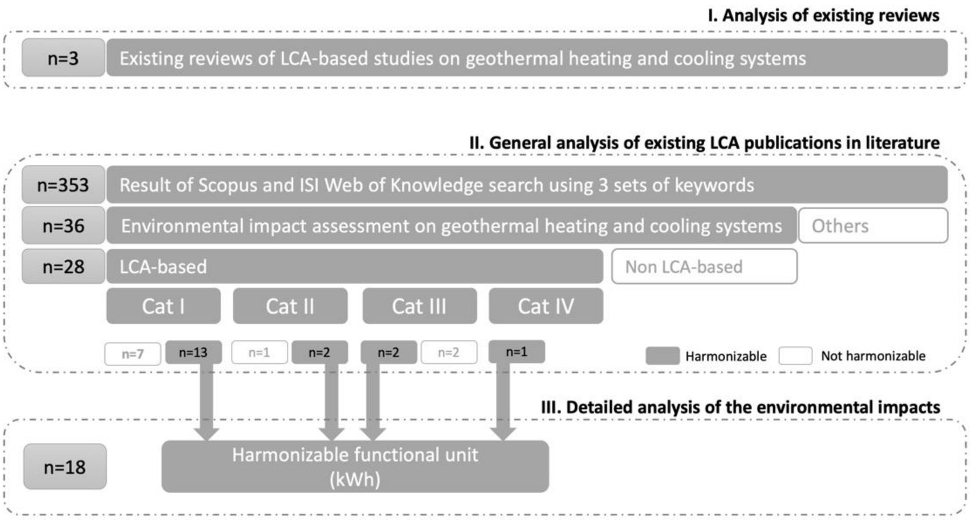

Figure 1. Literature review methodology

These publications cover a wide range of applications that use geothermal energy and therefore categories were made to allow a comparative analysis (Figure 2). A report from European Geothermal Energy Council (2019) was used as a proxy to establish the criteria for the categorization. EGEC grouped a large number of heating and cooling systems installations in Europe in two groups: fields of borehole heat exchangers and district heating plants. District heating plants include a variety of applications where groundwater is extracted at different temperatures. Two more categories were established in order to refine the assessment and include heat utilization in industry. An additional category that corresponds to geothermal for electricity production was also added, so that the full extent of LCA literature for all types of geothermal systems can be observed. Five categories were finally established as a function of the enthalpy of the geothermal resource, the medium of heat extraction, and the process of heat utilization at the surface (Figure 2). Geothermal heating and cooling installations in Europe were grouped into the same categories to allow comparison between the numbers of LCA publications and the numbers of installations in Europe (European Geothermal Energy Council, 2018).

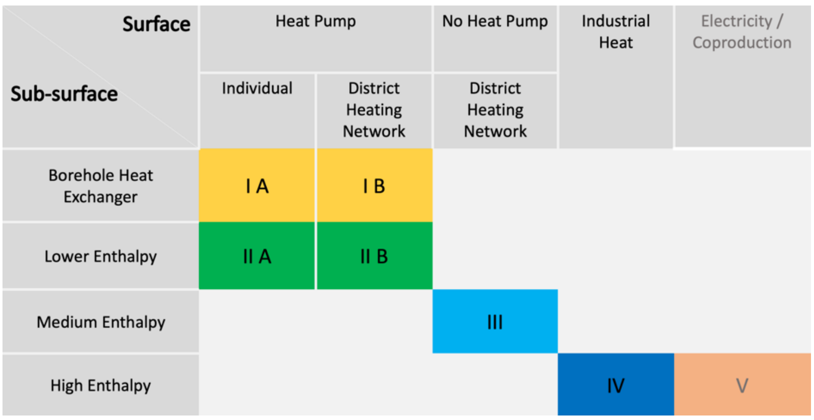

Figure 2. Categories of geothermal systems reported in LCA studies

The characteristics of each category from Figure 2 are detailed as follows:

- **Category I.** The system consists of borehole heat exchangers (BHE) and a heat pump. The depth of the BHE could reach up to 200 m. The system relies on constant ground temperature, where a closed-loop fluid circulation exploits the underground heat. Depending on the depth and the number of BHE, the system could supply both heating and cooling to an individual house (IA) as well as a group of buildings by means of district heating networks (IB).
- **Category II.** The system extracts groundwater at a temperature where the heat pump will still be necessary for it to be able to supply the heat demand. The depth of the well of this category varies from 30 m to 1500 m. Similarly, it could supply heating and cooling to individual houses (II A) as well as to a more extensive district heating network (II B).
- **Category III:** The system extracts groundwater at a temperature that is enough to fulfill heating demand without a heat pump. Such temperature is obtained typically from a greater depth, such as the geothermal heating system at Orly Airport in Paris that extracts 74°C water from a depth of 1700 m.
- **Category IV**: The system aims to serve industrial processes that often require a temperature that is higher than for residential space heating. The system extracts water from a much greater depth and, in some cases, it may need permeability enhancement measures, like in the case of Enhanced Geothermal System (EGS). For example, in Rittershoffen in France, 170°C brine is extracted from granitic rocks at a depth of 3196 m.
- **Category V:** The characteristics of the subsurface for electricity production are similar to the previous category, even

though in some areas geothermal resources have a much higher enthalpy. The thermal energy is converted into electricity via an Organic Rankine Cycle, Kalina Cycle, or Flash system.

For detailed analysis of the environmental impacts (Figure 1), the reported impacts were documented and, for quantitative analysis, harmonized into one functional unit, which is a unit of *impact/kWh*. Some publications, however, employed methodologies that prevent the results from being compared with other studies and such publications were excluded. Finally, in the last part, only 18 system designs from 17 publications were analyzed.

3. RESULTS AND DISCUSSIONS

3.1. Analysis of existing reviews

Existing reviews mostly discussed studies of geothermal systems with heat pumps. Marinelli et al. (2019) carried out a critical review of life cycle thinking for residential heat pumps. After applying some selection criteria, 17 studies conducting life cycle assessments of environmental impacts, costs, and social impacts were investigated. The ground-coupled heat pumps and groundwater heat pumps were found to be the two most studied systems. This review also reported that LCA publications often excluded the maintenance stage from the scope of the study. Lack of data and the assumption that this stage has negligible impacts were the two main reasons. This review also reported that the operational phase contributes on average to around 50% of the negative environmental impacts, principally owing to the electricity use in heat pumps. In this regard, two aspects were acknowledged to be essential parameters: the electricity mix and the seasonal performance factors (SPF).

Bayer et al. (2012) further assessed the consequences of the interaction of these two parameters on life-cycle greenhouse gas (GHG) savings across different countries in Europe, resulted from substituting the existing heating systems by GSHP. They also considered the countries' heating mix in the calculation. They showed that, for some countries, there is a minimum threshold of SPF below which GHG savings cannot be accomplished. In Poland, the electricity mix has an average carbon emission rate of 1.18 $kgCO_2/kWh$, and the carbon emission of the substituted heating mix is 1123 $kgCO_2/kJ$. The minimum SPF to achieve GHG savings in this country was calculated to be as high as 3.8. The calculated SPF thresholds for Netherland and Germany were 3 and 2.4 respectively.

In the initial stage of their study, Saner et al. (2010) reviewed 16 LCA publications on GSHP that quantified GHG savings. The range of savings varied greatly from 30% to 80% when compared to the different existing heating or cooling systems (e.g., chiller, gas boiler, oil boiler, wood combustion, air conditioner, and air source heat pump). Saner et al. (2010) also concluded that CO_2 emissions from primary energy consumption for heat pump operations are most crucial for GSHP systems. The study also suggested the potential increase in GHG savings from 30% to 55%, by considering additional use of GSHP to provide passive cooling in warm countries.

Another group of existing literature reviews of LCA of geothermal energy include electricity production. Tomasini-Montenegro et al. (2017) reviewed 21 LCA publications and divided them into four categories: dry steam, single and double flash, binary systems, and systems involving EGS. They reported that, regardless of the type of the system, the energy involved in the construction of wells is the main factor responsible for global warming impacts. Eberle et al. (2017) performed another review of LCA-based GHG emissions from geothermal electricity production. After applying specific selection criteria, 29 out of 180 LCA publications were investigated for three categories of systems: high-temperature flash, high-temperature binary, and EGS binary systems. The first category was found to emit the highest amount of GHG and the second category – the least.

The reviews above also pointed out the limitations of LCA concerning geothermal applications. Standardized LCA cannot quantify processes how the soil conditions alter due to the change in soil temperature (Marinelli et al., 2019). There is also a gap of LCA in reflecting impacts to the groundwater (Saner et al., 2010). Tomasini-Montenegro et al. (2017) reported that land use and seismicity had been rarely analysed. Finally, to our knowledge, no prior study comprehensively reviewed the existing LCA studies on all possible geothermal heating and cooling applications covering all enthalpy range.

3.2. General analysis of existing LCA publications

In our review, 25 publications were selected to be analyzed because the authors quantified the environmental impacts using LCA methodology. These publications developed in total 28 system designs, of which the majority represent the geothermal cases in European countries. LCA studies on systems in China, South Korea, Japan, and Canada were also found. Eleven system designs, all corresponding to GSHP systems, took into consideration cooling systems, but no study included passive cooling. After classifying the studied geothermal systems into the categories from Figure 2, the ranges of temperatures and depths were identified and summarized in Table 1. Figure 3 shows a relative comparison between the number of LCA studies conducted worldwide for various categories of geothermal systems and the number of installed geothermal heating plants in Europe.

Table 1. Number of system designs, range of depth and temperature reported in the literature

Category	I	II	III	IV	V
Range of reported temperatures (°C)	n.a.	15	85-100	170	125-260
Range of reported depths (m)	80-234	55 - 1985	855 - 3000	3196	660 -5500
Number of system designs	20	3	4	1	41

Most studies in the literature were found to focus on the electricity production (Category V). For heating systems, however, most of the publications concentrated on Category I. It is evident from Figure 3 that there is a lack of research to study the systems of Category

II and III despite their popular deployment in many European countries, such as France, Germany, Hungary, and Iceland (European Geothermal Energy Council, 2018). Due to the wide range of depths and temperatures, these systems inherit considerable variability. Thus, in the context of policy making, it is imperative that such systems are analyzed in greater detail to quantify their environmental consequences. Additionally, there is indeed only one study in LCA literature concerning Category IV. This lack of publications on Category IV is consistent with the small amount of installations within this category.

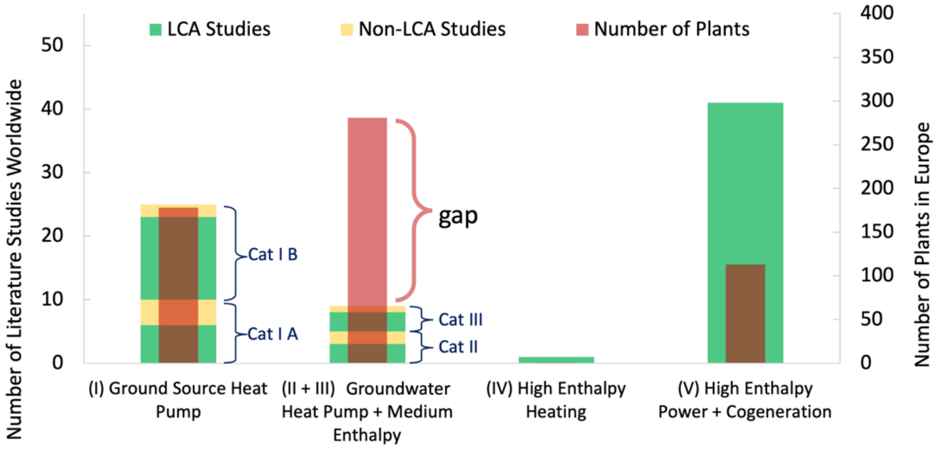

Figure 3. Number of installed plants in Europe vs. number of literature studies found worldwide

3.3. Scope and methodologies

Despite the established ISO 14040 standard, no universal methodology can be identified in LCA literature. This section identifies and discusses several methodological differences and similarities in the publications.

The first observed dissimilarity referred to the Life Cycle Impact Assessment (LCIA) methodologies. The elements of LCIA methodologies include the selection of impact categories, category indicators and models, the assignment of life cycle inventory to the impact category (classifications) and the calculation of category indicator results (characterization) (Reap et al., 2008). There are many established and internationally recognized methodologies in the LCA literature. In our review, no single LCIA methodology was found to be dominant. CML[1]-based methodologies were employed by seven studies, while other recognized midpoint LCIA methodologies (ILCD[2], IMPACT 2002+[3], and ReCiPe 2008[4]) were used equally frequently. Three publications applied endpoint methodology, so-called Eco-Indicator 95 or Eco-Indicator 99, and this made comparison impossible. These studies were therefore omitted from the detailed analysis in Section 4. Because each LCIA methodology uses different approaches to model their characterization factors only some comparative analysis could be conducted (Table 2). Concerning the impacts on resource depletion, eutrophication, and acidification, investigations were carried out only on publications employing CML-based methodologies. On the other hand, investigation on ozone depletion included more publications. There is no other recognized methodology to quantify global warming potential (GWP) than the one from IPCC. Thus, all studies were considered.

The second dissimilarity concerned the choice of the functional units. The impact factors were reported in various functional units: for example, GWP was expressed in gCO_{2eq}/kWh, gCO_{2eq}/MJ, gCO_{2eq}/household/year, gCO_{2eq}/building, etc. To allow evaluating the outcomes in our subsequent analysis, harmonizing the functional units was necessary. One kWh of heat produced for heating or extracted for cooling was chosen as the harmonized functional unit. We omitted publications that do not contain enough information to allow conversion of the quantified impacts from their original functional unit to the harmonized one.

The last dissimilarity was found in the definition of the scope of the studies. Around 60% of the studies disregarded the end-of-life phase in their analysis and exploration activities are never considered even in the hydrothermal systems. An exception is the study by Pratiwi et al., (2018), who considered seismic acquisition activity that contributed 0.14% to the total life-cycle CO_2 emissions. On the other hand, Marinelli et al. (2019) stated that end-of-life stage of a heat pump on average covers 5% of the total CO_2 emissions. Therefore, neglecting exploration or end-of-life phase is considered acceptable.

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[1] CML: A Characterization Factor (CF) database developed by Leiden University
[2] ILCD: A CF database released by the Joint Research Centre of the European Commission, combining the methodologies reported in the International Reference Life Cycle Data System
[3] IMPACT 2002+: A CF database developed by EPFL in Lausanne, containing 1500 life cycle inventory results.
[4] ReCiPe 2008: A CF developed as harmonization between CML and Eco-indicator 99, developed by PRé Consultants B.V.

Table 2. Modelling approach for each LCIA methodologies and the associated studies

	Midpoint					Endpoint
	CML (1992, 2000, 2001)	RECIPE (2008)	ILCD	IMPACT 2002+	Other studies (LCIA Methodology)	Eco Indicator
Studies on Category I	Greening & Azapagic, 2012; Russo et al., 2014; Martín-Gamboa et al., 2015 ; Péricault et al., 2018 ; Hong et al., 2016	Saner et al., 2010 ; Bonamente & Aquino, 2017	Bartolozzi et al., 2017	Ghafghazi et al., 2011 ; Rodriguez et al., 2012	Ristimäki et al.,2013 (Envimat); Kim et al., 2015 (Environnemental Labelling III); Blum et al., 2010 (GEMSI); Chang et al., 2017 (U.S. EPA‘s AP-42); Genchi et al., 2002 (Japan Statistics and Documentation)	Nitkiewicz & Sekret, 2014; Koroneos & Nanaki, 2017
Studies on Category II	Kaltschmitt, 2000	Kljajić et al., 2018			Liu, 2017 (China Statistics and Documentation)	
Studies on Category III	Kaltschmitt, 2000; Karlsdottir et al., 2014				Guo et al., 2013 (IPCC 2007)	Benke & Pátzay, 2010
Studies on Category IV			Pratiwi, et al., 2018			
Global Warming Potential	GWP from IPCC					
Ozone Depletion	Ozone Depletion from WMP					
Resource and Fossil Fuel Depletion	Guinee and Heijungs, 1995	Kirkham & Rafer, 2003	Schneider et al., 2015; Hischier et al., 2010	Based on Eco-Indicator		
Eutrophication	Non-mechanistic fate model.	Mechanistic fate model EUTREND and CARMEN.		Fate model based on Helmes et al. (2012) and GEOSchem		
Acidification	Huijbregts et al., 2000	Van Zelm et al., 2007a	Seppällä et al., 2006 ; Posch et al., 2008	Roy et al., 2021a, 2012b, 2014		

3.4. Detailed analysis of the environmental impacts per category

Category I

This section explores the relative behavior of the environmental impact factors reported in the literature per category of geothermal system and their dependence on the input parameters. Under Category I, there are 20 LCA studies and 13 of them are harmonizable. The impact factors analyzed are featured in Figure 4. Plotted alongside them are the impacts of small-scale oil boilers[5]. Except for two studies, Category I systems have lower GWP than small-scale oil boilers. But we could observe that, in terms of fossil fuel consumption, ozone depletion, and acidification potential, the environmental impacts of small-scale oil boilers are not always more severe than the systems in Category I. It also implies that focusing LCA merely on GWP would prompt misinterpretation of the system’s full environmental sustainability performance.

[5]The activities are based on Ecoinvent 3.3 database, referring to the process: *heat production, light fuel oil, at boiler 100kW condensing, non-modulating”*. The impacts were calculated using CML Baseline characterization factors.

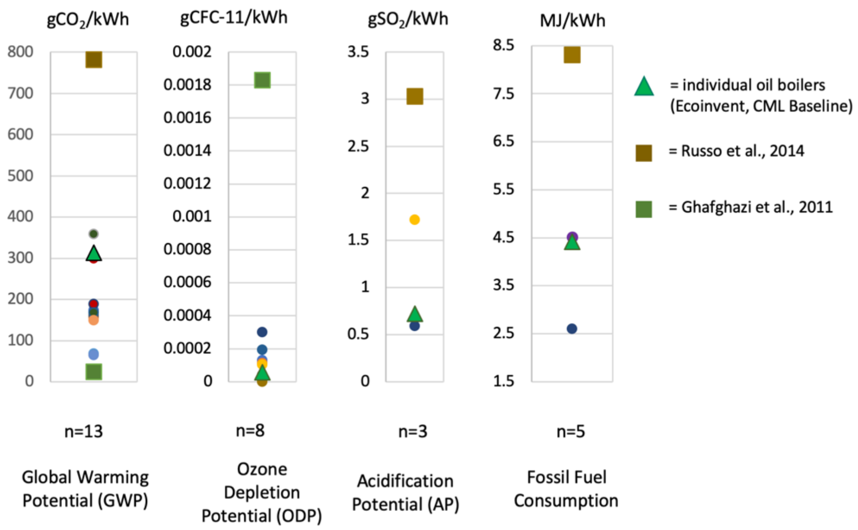

Figure 4. Environmental impacts of Category I

The impacts evaluated by Russo et al. (2014) are observed as outliers for GWP. The values are significantly higher than in other studies analysed. Their study exclusively refers to the geothermal application for a greenhouse in Bari, Italy. The electricity mix assumed in the study is dominated by thermal power plants and could explain the high estimates. However, there is no information with regards to the composition of the electricity mix and its emissions assumed by the authors. Another observation is the high level of ozone depletion potential reported by Ghafghazi et al. (2011). They assumed the use of HCFC[6] (having ODP[7] equal to 0.55) as the refrigerant and acknowledged this fluid as the contributor to ozone depletion. Other studies assumed R134a, having ODP equal to 0, which put their ozone depletion impact at lower levels.

Closer attention was given to understand the distribution of the GWP across the literature. Previous studies on Category I systems unanimously concluded that, throughout a lifetime of the system, their use phase contributes the most to GWP. It is true for our review, except for the publication from Koroneos & Nanaki (2017), where a calculation error was observed. Thus, the essential factors impacting GWP are the ones involved in the use phase. Greening & Azapagic (2012) conducted sensitivity analyses of environmental impacts of heat pumps as a function of the changes of COP and electricity mix carbon intensity. It suggested that introducing an 80% share of renewable technologies into UK electricity mix in 2012 would reduce the GWP impact by 50%. Increasing SPF (equivalent to annual average COP) from 3.9 to 6 and keeping the electricity mix constant would reduce the GWP impact by 33%. The conclusion of this analysis is consistent with the findings discussed in Section 0. Saner et al. (2010) complemented these two parameters with the leakage rate of refrigerant, assuming the use of R134a. They concluded that for countries with high carbon intensity in the electricity mix, this leakage would contribute insignificantly to the increase of GWP (e.g. it introduced an increase of 3% in GWP for Poland).

Furthermore, there is no noticeable difference in the amount of GHG emissions per kWh between the systems providing only heating and the systems providing heating and active cooling. No publication in Category I analyzed a system involving passive cooling. Thus, the comparison with such applications could not be made.

Category II

Six publications that assess environmental impacts of geothermal systems in Category II were discovered. Three of them are LCA-based studies and only two of them reported kWh as the functional unit. Both studies reported the use-phase as the main contributor to the overall environmental impacts, even for a system with deep wells. Having electricity mix which relies on fossil fuels strengthens this argument. No previous study has investigated the case of an electricity mix without direct use of fossil fuels.

Kaltschmitt (2000) analyzed the benefit of integrating renewable energy, including solar thermal, biomass, and geothermal, into district heating in Germany. He developed three hypothetical scenarios according to the capacity of the system. One scenario, namely "Small District Heating System" with $3MW_{th}$ capacity was the one that would fall under Category II. The integration that he considered would mostly mean that the peak demand was met using oil or gas boilers, while geothermal systems provided the baseload. The figures for this scenario were 189 gCO_{2eq}/kWh, 0.64 SO_{2eq}/kWh, and 2.6 MJ/kWh for GWP, acidification potential,

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[6] Hydrochlorofluorocarbons

[7]ODP values are used to provide a simple way to compare the relative ability of various ozone depleting substance to destroy stratospheric ozone. UNEP defined ODP as *"the integrated change in total ozone per unit mass emission of a specific ozone-depleting substance relative to the integrated change in total ozone per unit mass emission of CFC-11"* (Agarwal & Clark, n.d). The value 1 corresponds to the ODP value of CFC-11, of which the consumption and production ended in 2010 worldwide. (Agarwal & Clark, n.d)

and fossil fuel consumption respectively. No detailed results were presented for the geothermal systems separately.

More recently, Liu (2017) evaluated a Hot Dry Rock geothermal system in China, which comprises three untypical wells with a depth of 1985 m, each having inner and outer tubes. The temperature at the bottom of each well reaches around 70°C. For each well, freshwater is injected through the annulus to extract the heat from underground and then flow upwards to the surface through the inner tube. A heat pump then lifts the temperature to meet the heat demand of the district heating. This geothermal system, though uncommon, falls under Category II thanks to its enthalpy. Liu (2017) reported a GWP of 82.36 gCO_{2eq}/kWh, acidification potential of 0.76g of SO_{2eq}/kWh and total energy consumption of 2.25 MJ/kWh.

Category III

Four publications in Category III were discovered. Among those, three are LCA-based studies and two are harmonizable to kWh. The first study presents another scenario from Kaltschmitt (2000), namely "Large District Heating System", that has a thermal capacity of 10 MW. As discussed previously, geothermal systems in this scenario are assisted by a gas or oil boiler to meet the peak demand. The study presented a range of environmental impacts, of which the lower bound represented the best geothermal characteristics: 90°C, operating without any heat pump, and minimal natural gas contribution. The parameters set for the upper bound were not precisely stated except for the fact that the peak demand was met by light oil.

Karlsdottir et al. (2014) investigated the district heating case in Stykkishólmur, Iceland. This system comprises a production well and an injection well 5 km and 4 km away respectively from the city, a heat exchanger station, and the distribution and house connection pipelines. The geothermal wells are 855 m and 819 m deep (Khalilabad & Axelsson, 2008). Additionally, the scope also includes the collection and reinjection pipelines that carry both hot water of 79°C to the district heating grid and back to the injection well at 35°C. Karlsdottir et al. (2014) suggested that these transport pipes contribute significantly to the environmental impacts, followed by the use of fuel and bentonite during drilling. They reported environmental impacts of 5.8gCO_{2eq}/kWh, 0.1MJ/kWh, and 0.029 gSO_{2eq}/kWh for GWP, fossil fuel consumption, and acidification respectively.

Category IV

In Category IV, only one LCA publication was found. Pratiwi et al. (2018) reported a case of industrial EGS plant in Rittershoffen in France, that supplies heat to a biorefinery 15 km away from the plant. Geothermal brine of 170°C is extracted from a production well of 3196 m and reinjected at 70°C into another well of 2508 m. 52% of the life cycle CO_2 emissions were caused by the construction process, including the transportation pipe. Another 23% come from the operation phase and are largely attributable to electricity consumption. The study reported an average GWP of 8 gCO_{2eq}/kWh if the transport pipes are included and 5.55 gCO_{2eq}/kWh otherwise. No other environmental impacts were reported.

Figure 5 summarizes the environmental impacts of the reviewed geothermal systems in Category II, III, and IV along with the comparison with small-scale oil boilers. The lower and upper bound of the emissions calculated by Kaltschmitt (2000) for Category III are represented by red bars. Predominantly, despite the different scope within each study, the environmental impacts of Category II are relatively higher than the Category III and IV. When compared to small-scale oil boilers, it appears that these systems have lower environmental impacts, even when both studies in Category II rely on thermal plants for their electricity mix. However, the number of studies is too small for any conclusions to be made.

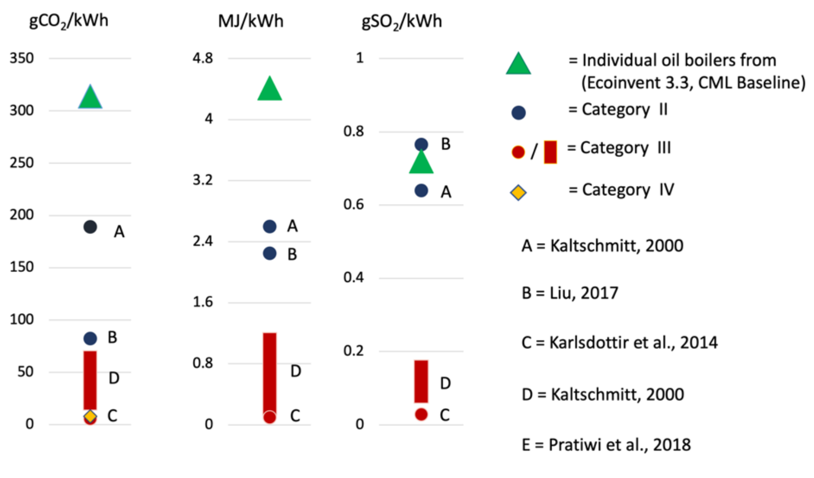

Figure 5. Environmental impacts of systems in Category II, Category III and small-scale oil boilers

3.5. Uncertainty and variability

For many reasons, the authors of the reviewed literature could not always rely on accurate data and had to make assumptions for unknown information. It is a usual practice in LCA and it requires uncertainty and sensitivity analyses. Hong et al. (2016) addressed uncertainty through sensitivity analysis, using a unitless indicator called sensitivity influence coefficient. They evaluated only subsurface design factors as the input parameters (e.g., borehole length, spacing, diameter, grout conductivity) and observed the energy generation and environmental impacts as the output. They found that borehole length has the most influence. Pratiwi et al. (2018) dealt with the uncertainty through Monte Carlo simulation, appraising both the foreground uncertainties using pedigree matrix and background uncertainties provided by Ecoinvent 3.3 database.

Variability, on the other hand, was more often evaluated in the literature. Variability represents the spread of data of a parameter. Unlike uncertainty, this information is known. To address variability, Saner et al. (2010) conducted a sensitivity analysis for Category I, representing a leak of refrigerant, a leak of heat carrier, COP degradation, and carbon intensity of electricity mix. Different climates were also considered when they analyzed the range of potential CO_2 emission savings for countries in Europe. Another sensitivity study for Category I by Greening & Azapagic (2012) observed how the environmental impacts evolve after introducing changes in renewable share in the electricity mix as well as in heat pump SPF.

Analyses to address uncertainty and variability for other categories of geothermal systems were not discovered and remain to be conducted. As mentioned in previous section, Category II and III inherit large variability in their input parameters. Several examples of parameters that have high influence and high range are depth, temperature, and flowrate.

3.6. LCA perspective in the context of geothermal potential in Geneva

In Switzerland, geothermal systems of Category I are the most common systems. In 2008, they already constituted around 75% of geothermal energy in the country (Groupe de Travail PGG, 2011). In Geneva in 2010, around a thousand borehole heat exchangers were deployed with typical depths of 100 m - 200 m (Groupe de Travail PGG, 2011). Category I is a mature system by now in Switzerland. With regards to Category II, the temperature of groundwater in Geneva's shallow aquifers varies from 8°C to 23°C depending on the depth and season. The top of these shallow aquifers varies from 15 m to 60 m (Groupe de travail PGG, 2011). The additional value from exploiting this source is the opportunity to apply passive cooling. Aquifers at greater depth are estimated to have higher temperatures, for example, in cretaceous formation which could reach 1.8 km depth, the temperature is estimated to be around 10°C – 65°C. In Malm or Dogger formation, whose depth could reach 3.4 km, the temperature could be up to 112°C. In Muschelkalk formation, the temperature would vary from 93-141°C. At this point, the system would fall into Category III where no more heat pump would be necessary. The estimations made for geothermal systems at these depths entail a high degree of uncertainty due to the lack of data. Detailed investigation through geophysical campaign or exploration drilling is necessary to reduce this uncertainty and this is the main objective of GEothermie 2020. Within its timeline, the program looks into creating geothermal pilot projects representing three ranges of depth: 0 m – 100 m, 500 m – 1500 m, 1500 m – 3000 m. The program also aims to create prospection for systems with a depth of 3000 m or more (GEothermie 2020, n.d.).

Higher reservoir temperatures which could meet industrial needs (Category IV) or electricity production (Category V) would necessitate EGS in the Swiss context. A project called GGP Genève was started in 1998 with an objective to acquire 200°C temperature at a depth of 5 km - 6 km. However, before any drilling could start, this project was halted following induced seismicity that occurred in a parallel project in Basel in 2006 (Groupe de Travail PGG, 2011). As a matter of fact, induced seismicity is a prominent risk linked to EGS and needs to be minimized (Trutnevyte & Wiemer, 2017). Simply siting an EGS project far from the urban area will not be the most economical solution. Doing so would reduce the possibility of selling heat energy to the inhabitant (Knoblauch & Trutnevyte, 2018).

Future LCA studies for geothermal systems in Geneva need to represent Category II and III at various depths and temperatures rather than Categories I and IV, for which plentiful literature already exists. The planned LCA for Category II and III systems in Geneva will also fill the gap in the wider scientific literature, as mentioned in Section 3.2. Moreover, if the LCA studies need to be performed based on hypothetical cases, uncertainty and variability analyses will be critical.

4. CONCLUSIONS

This conference paper reviewed the state-of-the-art LCA studies on environmental impacts of geothermal heating and cooling systems, including three previous reviews on geothermal heating systems with heat pumps and 25 publications from a systematic literature search on ISI Web of Knowledge and Scopus. We found that most studies focused either on shallow geothermal applications with heat pumps or on high enthalpy EGS systems for electricity production. The comparison between the number of LCA studies and the existing heating and cooling installations in Europe showed that there is a lack of LCA studies for geothermal systems in Category II and III (i.e., the systems that extract groundwater for medium depths with or without heat pumps) despite their wide deployment. Therefore, we suggest performing LCA for these types of systems in the future.

Furthermore, we observed that global warming potential is the impact factor that was examined by all authors. For systems with heat pumps, the operation phase contributed significantly to the environmental impacts as well as the electricity mix and COP or SPF. After studying in detail the publications to which harmonization could be applied, we found that the publications for geothermal systems of Category II and III indicated that their environmental impacts are less severe than those of small-scale oil boiler. However, the number of studies was too low for any definite conclusions to be made. For Category I systems, there is unclear evidence whether these systems perform better than small-scale oil boilers. It implies that performing LCA merely on GWP could lead to misinterpretation of the system's overall environmental sustainability.

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