Systematic Review of Life Cycle Greenhouse Gas Emissions from Geothermal Electricity

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Scott Nicholson, and Alberta Carpenter
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Executive Summary

The primary goal of this work was to assess the magnitude and variability of published life cycle greenhouse gas (GHG) emission estimates for three types of geothermal electricity generation technologies: enhanced geothermal systems (EGS) binary, hydrothermal (HT) flash, and HT binary. These technologies were chosen to align the results of this report with technologies modeled in National Renewable Energy Laboratory's (NREL's) Regional Energy Deployment Systems (ReEDs) model. Although we did gather and screen life cycle assessment (LCA) literature on hybrid systems, dry steam, and two geothermal heating technologies, we did not analyze published GHG emission estimates for these technologies.

In our systematic literature review of the LCA literature, we screened studies in two stages based on a variety of criteria adapted from NREL's Life Cycle Assessment (LCA) Harmonization study (Heath and Mann 2012). Of the more than 180 geothermal studies identified, only 29 successfully passed both screening stages and only 26 of these included estimates of life cycle GHG emissions. We found that the median estimate of life cycle GHG emissions (in grams of carbon dioxide equivalent per kilowatt-hour generated [g CO_2eq/kWh]) reported by these studies are 32.0, 47.0, and 11.3 for EGS binary, HT flash, and HT binary, respectively (Figure ES-1).

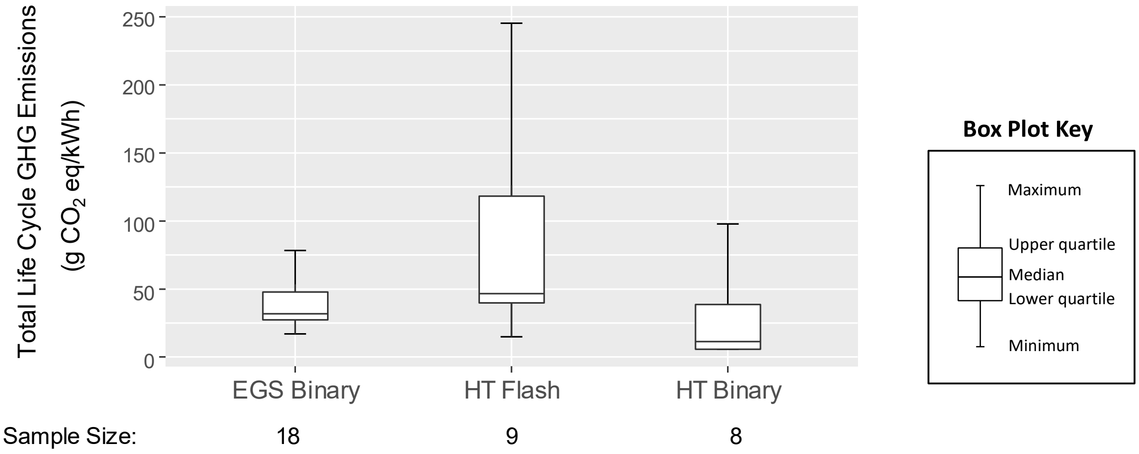

Figure ES-1. Life cycle greenhouse gas emissions (GHG) for three types of geothermal electricity: enhanced geothermal systems (EGS) binary, hydrothermal (HT) flash and HT binary.

We also found that the total life cycle GHG emissions are dominated by different stages of the life cycle for different technologies. For example, the GHG emissions from HT flash plants are dominated by the operations phase owing to the flash cycle being open loop whereby carbon dioxide entrained in the geothermal fluids is released to the atmosphere. This is in contrast to binary plants (using either EGS or HT resources), whose GHG emissions predominantly originate in the construction phase, owing to its closed-loop process design. Finally, by comparing this review's literature-derived range of HT flash GHG emissions to data from currently operating geothermal plants, we found that emissions from operational plants exhibit more variability and the median of emissions from operational plants is twice the median of operational emissions reported by LCAs. Further investigation is warranted to better understand the cause of differences between published LCAs and estimates from operational plants and to develop LCA analytical approaches that can yield estimates closer to actual emissions.

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Introduction

Thermal energy stored in rock, steam, or liquid water can be extracted and used in thermal power plants to produce electricity, heat, or combined heat and power. Although some direct uses of geothermal energy, such as bathing in hot springs, have been used for thousands of years (Cataldi 1999), geothermal power generation technologies were not developed until the early 1900s (Burgassi 1999).

The first geothermal power plant used dry steam that came directly out of a geofield found in Lardarello, Italy. Geothermal power generation methods now include hydrothermal systems and enhanced geothermal systems (EGSs). Hydrothermal (HT) methods bring in-situ geofluids from naturally-occurring geothermal reservoirs to the surface to power a turbo generator either (1) indirectly in a binary cycle plant, which passes the geofluid through a heat exchanger using a secondary working fluid to turn the generator or (2) directly in a flash plant, where the geofluid is vaporized to generate steam which turns the generator. An EGS uses the same power generation method via a turbo generator with binary or flash technology. However, an EGS uses hydraulic stimulation to create fluid connectivity in geothermal systems that do not have adequate water or permeability.

Geothermal energy presents several advantages over other renewable energy technologies, including that it can provide year-round baseload power. However, in 2015, geothermal energy only comprised approximately 0.2% of the world's primary energy supply (Lund and Boyd 2016, EIA 2016), including 73 terawatt-hours of geothermal electricity (Bertani 2016). Despite the current limited use of geothermal resources, estimates of the global technical potential indicate that geothermal resources could comprise anywhere from 127 exajoules/year to 1,420 exajoules/year, or 25%–280% of the world's 2008 energy consumption (IPCC 2011). The large range of these estimates is due to variations in technological advances, including the ability to commercialize EGSs, which would allow access to potential resources at greater depths and in more geographic regions.

Motivation

With its abundance and reliability, geothermal energy presents opportunities for reducing the world's dependence on fossil fuels for power and heat generation. In addition, because geothermal power plants have been shown, in almost all cases, to have lower greenhouse gas (GHG) emissions than fossil fuel-fired power plants (Sullivan et al. 2010), they could also help mitigate climate change impacts. However, estimates for the environmental impacts of geothermal power plants vary considerably. In some cases, the estimates of GHGs emitted per kilowatt-hour of geothermal electricity are five to ten times larger than the median values reported for wind and solar technologies (IPCC 2011).

Although authors of many prior studies have performed life cycle assessments (LCAs) to evaluate the environmental impacts of geothermal energy, only two have compared the results from multiple studies (Sullivan et al. 2010; IPCC 2011). Sullivan et al. (2010) developed an LCA for geothermal power plants and compared their results to five other studies, but they did not comprehensively review all available LCAs. Researchers at the National Renewable Energy Laboratory (NREL) systematically reviewed 46 geothermal LCAs in 2011 in support of the Intergovernmental Panel on Climate Change (IPCC) Special Report on Renewable Energy Sources and Climate Change Mitigation (SRREN) (IPCC 2011). For the 2011 IPCC SRREN, only nine published studies passed the screening process of NREL's LCA Harmonization Study (Heath and Mann 2012) and, of those, only six provided estimates of life cycle GHG emissions.

Several new LCAs of geothermal technologies have been published since IPCC (2011) and Sullivan et al. (2010). The goal of this work is to build on prior work by incorporating the latest studies in order to decrease the uncertainty around these estimates and increase their value for research and policymaking. Thus, we performed a thorough review of the LCA literature regarding environmental impacts associated with geothermal technologies and then screened the resulting studies using the similar methods to those employed in NREL's LCA Harmonization Study (Heath and Mann 2012).

Methodology

The methods for this current comprehensive literature review were adapted from Heath and Mann (2012) and include a series of two screens. The first screen evaluates whether the study:

- Is written in English;
- Was published after 1980;
- Was published as:
  - An archival journal article or trade journal article greater than three published pages in length,
  - A conference proceeding greater than five double-spaced pages in length, or
  - A book or book chapter, thesis, dissertation, or report;
- Covers geothermal energy; and
- Reports quantitative results from an LCA or reviews results from multiple LCAs.

The second screen, as outlined in Table 1, evaluates the quality, transparency, completeness, and relevance of the studies that pass the first screen.

Table 1. Criteria Used to Perform the Second Screen, which Evaluated the Study's Quality, Transparency, Completeness, and Relevance

Category for Second Screen	Criteria
Quality	Uses a currently accepted LCA method (e.g., follows guideline 14040 from the International Organization for Standardization (ISO 2006))
	Employs a relevant impact assessment method (e.g., selected impact categories, category indicators, and characterization methods)
	Evaluates at least two life cycle stages
Transparency and Completeness	Reports their method transparently with regard to key parameters, assumptions and methods (e.g., defines a system boundary)
	Provides a numerical description of the system characteristics (e.g., plant size or well depth)
	Reports the environmental impact estimates quantitatively
	If appropriate, reports the name of LCA software or database used for the analysis
	Provides citations for data sources
	Reports a unique estimate of the result (i.e., the result is not cited from prior work)
	Provides enough information to scale results by plant generation
Relevance	Evaluates a modern or near-future system (e.g., supercritical carbon dioxide [CO_2] as a working fluid). Geo-pressured geothermal systems were excluded.

After screening the literature, we compiled data from studies that passed all criteria in both screens and also reported estimates of life cycle GHG emissions from geothermal electricity generated by three technology types: EGS binary, HT flash, and HT binary. We did not compile water use estimates from any study because detailed analysis of water use was outside the scope of this work, nor did we compile GHG emission estimates for direct use heating, hybrid, and dry steam systems because those technologies are not modeled within NREL's Regional Energy Deployment System (ReEDS) model.

For the three types of geothermal electricity investigated, we computed the central tendency and variability in published estimates of GHG emissions for the total life cycle and by life cycle phase (i.e., construction, operation, and end-of-life). If the sample size for the estimates was greater than four, we computed the central tendency using the median and the variability using the interquartile range (i.e., the spread of the middle 50% of the estimates; lower and upper quartiles correspond to the 25th and 75th percentiles respectively) and the total range (i.e., minimum and maximum values). We used these statistics to generate box plots of the total and phase-disaggregated life cycle GHG emissions for the three technology types. These estimates are compatible with ReEDS modeling of life cycle GHG emissions for future power sector deployment scenarios such as for Vision studies performed by the U.S. Department of Energy (DOE) (*Wind Vision*, *Hydropower Vision*, etc.) (DOE 2015; DOE 2016).

There are several differences between this report and NREL's prior harmonization studies of other energy technologies. First, unlike prior NREL harmonization studies, this work only performs a systematic review of the literature and compiles the resulting estimates for life cycle GHG emissions. We do not harmonize the estimates to reflect consistent performance characteristics, life cycle stages, or global warming potentials because such an analysis was outside the scope of this work. Second, to build broad knowledge of the life cycle impacts of geothermal energy, we do not limit our literature survey to only GHG emissions. Instead, we also include studies that report water use (Table 2).

Results and Discussion

To build broad knowledge of the life cycle impacts of geothermal energy and to assist future researchers in identifying literature on these topics, we initially performed a literature search, which in addition to identifying LCAs containing estimates of life cycle GHG emissions also identified LCAs containing estimates of life cycle water use. For the same reasons, we also initially searched more broadly on a technology basis than the three geothermal technologies that this report focuses its analysis on. The initial technologies included:

- Electricity generated by
    1. EGS binary: EGSs used in the operation of binary cycle power plants,
    2. HT binary: HT resources used in binary cycle plants,
    3. HT flash: high-temperature HT resources that are vaporized and used in flash steam plants,
    4. Dry steam: steam that directly drives a turbine, and
    5. Hybrid systems: the combination or two or more electricity generation technologies (e.g., geothermal and solar); and
- Heat generated by
    6. Combined heat and power: simultaneous production of heat and electricity from geothermal energy, and
    7. Geothermal heat pumps: pumps that transfer heat to or from the ground.

We then focused our analysis on GHG emissions from geothermal electricity and analyzed the three geothermal electricity generation technologies for which multiple LCAs had been performed and which align with the technologies modeled in NREL's ReEDS model: EGS binary, HT binary, and HT flash.

Of more than 180 geothermal environmental impact studies identified through our systematic review procedures of this literature, only 82 passed the first screen and 29 of those passed the second screen (Table 2). The 29 studies that passed both screens produced more than 40 estimates for two types of environmental impacts – GHG emissions and water use. Three of the studies we identified were included in the comparison performed by Sullivan et al. (2010) (italicized and highlighted in grey in Table 2). Five of the studies were also reported by NREL in the IPCC SRREN (2011) (listed in bold in Table 2).

Table 2. Studies that Passed both Screens and Produced an Estimate for the Life Cycle Environmental Impact of Geothermal Energy[a]

Technology Type	Author and Year	Publication Type	Type of Environmental Impact
EGS binary	**Rogge and Kaltschmitt 2003**	**Journal article**	**GHG emissions**
	Bauer et al. 2008	Conference paper	GHG emissions
	Frick et al. 2010	***Journal article***	***GHG emissions***
	Clark et al. 2011	Report	Water use
	Clark et al. 2013	Report	Water use
	Heberle et a. 2016	Journal article	GHG emissions
	Lacirignola and Blanc 2013	Journal article	GHG emissions
	Meldrum et al. 2013	Journal article	Water use
	Sullivan et al. 2013	Journal article	GHG emissions
	Sullivan et al. 2014	Report	GHG emissions
	Treyer et al. 2014	Journal article	GHG emissions
HT binary	***Rule et al. 2009***	***Journal article***	***GHG emissions***
	Clark et al. 2011	Report	Water use
	Clark et al. 2013	Report	Water use
	Meldrum et al. 2013	Journal article	Water use
	Sullivan et al. 2013	Journal article	GHG emissions
	Sullivan et al. 2014	Report	GHG emissions
	Martin-Gamboa et al. 2015	Journal article	GHG emissions
HT flash	***Hondo 2005***	***Journal article***	***GHG emissions***
	Karlsdottir et al. 2010a	**Conference paper**	**GHG emissions**
	Clark et al. 2011	Report	Water use
	Skone et al. 2012	Report	GHG emissions
	Clark et al. 2013	Report	Water use
	Marchand et al. 2015	Conference paper	GHG emissions
	Martínez-Corona et al. 2017	Journal article	GHG emissions
	Meldrum et al. 2013	Journal article	Water use
	Sullivan et al. 2013	Journal article	GHG emissions
	Sullivan et al. 2014	Report	GHG emissions
Combined heat and power	Karlsdottir et al. 2010b	Conference paper	GHG emissions
	Ruzzenenti et al. 2014	Journal article	GHG emissions
	Martin-Gamboa et al. 2015	Journal article	GHG emissions
Heat pump	Gilli et al. 1999	Report	GHG emissions
	Genchi et al. 2002	Journal article	GHG emissions
	Saner et al. 2010	Journal article	GHG emissions
	Ghafghazi et al. 2011	Journal article	GHG emissions
	Ristimäki et al. 2013	Journal article	GHG emissions
	Russo et al. 2014	Journal article	GHG emissions
	Kim et al. 2015	Journal article	GHG emissions
	Mattinen et al. 2015	Journal article	GHG emissions
Hybrid	Ristimäki et al. 2013	Journal article	GHG emissions
Dry steam	Buonocore et al. 2015	Journal article	GHG emissions

a) Grey coloring and italicized text highlights studies included in the comparison of life cycle greenhouse gas (GHG) emissions from geothermal electricity performed by Sullivan et al. (2010). Bold text corresponds to studies reported in the IPCC SRREN (2011). EGS = enhanced geothermal system, and HT = hydrothermal.

Overview of Estimates of Life Cycle GHG Emissions from Three Types of Geothermal Electricity

The primary goal of this work was to evaluate the life cycle GHG emissions associated with the two main types of geothermal energy currently used to generate electricity – hydrothermal (HT) and enhanced geothermal systems (EGS) – because these are the two types of geothermal electricity modeled in NREL's ReEDS model. As a result, we only extracted raw data from studies passing our screens for three technologies: HT binary, HT flash, and EGS binary. It is important to note that while EGS is considered a viable technology (DOE 2004), it is not yet commercialized and none of the LCA studies that passed our screens examined the total environmental impacts associated with EGS flash.

As shown in Table 3, the location, impact assessment methods, life cycle phases, lifetime, plant size, depth, and temperature evaluated for the three electricity generation technologies vary by study. The locations range from Germany to the United States and Japan, and the primary impact assessment method is based on the global warming potentials reported by the IPCC in 2007. The average operating lifetime is generally between 20 and 30 years, but one study (Rule et al. 2009) assumes 100 years. In addition, while all of these studies include the life cycle phases of construction and operation, some also include the impacts associated with exploratory drilling (exploration) and end-of-life (EOL). Although most studies report results for plant sizes of around 10 megawatts (MW), the sizes range from 900 kilowatts (kW) to 300 MW.

Limitations of this Work and Opportunities for Harmonization

As evidenced by the variations in the parameters employed by the LCA studies analyzed here, there are many opportunities for harmonizing the results to use similar global warming potentials, operating lifetimes, plant sizes, and system boundaries, as was done for most generation technologies evaluated in NREL's LCA Harmonization Study (follow hyperlink for complete list). However, the process of harmonization is outside the scope of this work.

It is also important to note that multiple environmental impact estimates are often reported by a single reference. For example, as indicated in Table 3, there are eighteen life cycle GHG estimates for EGS binary but they only come from seven different studies and ten estimates come from a single study by Lacirignola and Blanc (2013). Although these estimates explore the impact of depth and temperature, having multiple results from a single study may skew the overall results because of similarities in methods.

Table 3. Summary of Studies that Passed the Screening Criteria and Produced an Estimate of Life Cycle GHG Emissions for Three Types of Geothermal Electricity: Enhanced Geothermal Systems (EGS) Binary, Hydrothermal (HT) Binary and HT Flash

Author(s)	Year	Estimate Count	Location	Impact Assessment Method[b]	Inclusion of Life Cycle Phases[c]				System Lifetime (years)	Size (MW)	Depth (km)	Temp.[d] (°C)
					Explor.	*Constr.*	*O&M*	*EOL*				
EGS Binary Technology[a]												
Rogge and Kaltschmitt	2003	2	Germany	IPCC 1995		✓	✓	✓	-	0.9	3–4.5	150
Bauer et al.	2008	1	Switzerland	IPCC 2007		✓	✓	✓	30	36	5.5	150
Frick et al.	2010	2	Europe	Frick et al. 2010, Table 1	✓	✓	✓	✓	30	1.75	3.8–4.7	125–150
Lacirignola and Blanc	2013	10	Germany	IMPACT 2002+		✓	✓	✓	25	1–6	2.5–4	145–165
Sullivan et al.	2013	1	United States	IPCC 2007	✓	✓	✓		30	20	4–6	150–225
Sullivan et al.	2014	1	United States	IPCC 2007	✓	✓	✓		30	20	4–6	150–225
Treyer et al.	2014	1	Switzerland	IMPACT 2002+		✓	✓	✓	20	36	5.5	150
HT Binary[a]												
Rule et al.	2009	1	New Zealand	CO_2 only	✓	✓	✓	✓	100	162	0.66	200
Sullivan et al.	2013	1	United States	IPCC 2007	✓	✓	✓		30	50	< 2	150–185
Sullivan et al.	2014	1	United States	IPCC 2007	✓	✓	✓		30	10	< 2	150–185
Martin-Gamboa et al.	2015	1	Europe	CML-IA	✓	✓	✓	✓	25	2.9	0.725	150–162
Heberle et al.	2016	4	Germany	Heberle et al. 2016, Table 2	✓	✓	✓	✓	30	1.75	3.98	127
HT Flash[a]												
Hondo	2005	1	Japan	IPCC 1995 (CO_2 and CH_4)	✓	✓	✓		30	55	1	-
Karlsdottir et al.	2010a	1	Iceland	CML-IA		✓	✓		30	300	2.2	180
Skone et al.	2012	1	United States	IPCC 2007		✓	✓		25	50	3.2	182
Sullivan et al.	2013	1	United States	IPCC 2007	✓	✓	✓		30	10	1.5–3	175–300
Sullivan et al.	2014	1	United States	IPCC 2007	✓	✓	✓		30	50	1.5–3	175–300
Marchand et al.	2015	3	Guadeloupe	IPCC 2007	✓	✓	✓		30	16	> 0.5	250–252
Martínez-Corona et al.	2017	1	New Zealand	CML 2001	✓	✓	✓	✓	100	162	0.66	260

a) Technology types include enhanced geothermal systems (EGS) using binary technology (EGS binary), hydrothermal (HT) systems using binary technology (HT binary), and HT systems using flash technology (HT flash).

b) Impact assessment methods (global warming potentials) include those reported by IPCC (1995 and 2007), the IMPACT 2002+ method described by Humbert et al. (2014), and the CML-IA method from the Institute for Environmental Sciences at the University of Leiden (CML-IA 2016). The IMPACT 2002+ and the CML-IA methods both use characterization factors reported by the IPCC (2007).

c) The life cycle phases included in each study are indicated with checkmarks. "Explor." describes the exploration phase during which exploratory drilling occurs; "Constr." includes material extraction, processing, and plant construction; O&M refers to operation and maintenance; and EOL refers to end-of-life waste disposal and decommissioning.

d) "Temp." refers to the temperature of the resource in the ground, not at the surface.

Summary of Life Cycle GHG Emissions

Figure 1 shows the central tendency and variability of the life cycle GHG estimates from all studies that passed the first and second screens and reported life cycle GHG emissions for the three technology types examined here: EGS binary, HT flash, and HT binary (the specific studies are listed in Table 1; see Tables A-1 and A-6 in the appendix for summary statistics and raw data). By compiling results from multiple studies, this comprehensive review shows the range and distribution of values reported in the broader literature. However, it is important to note that the estimates reported here are not harmonized estimates because harmonization was outside the scope of this work. The median life cycle GHG emissions from EGS binary, HT flash, and HT binary plants were found to be 32 grams of carbon dioxide equivalent per kilowatt hour (g CO_2 eq/kWh), 47 g CO_2 eq/kWh, and 11.3 g CO_2 eq/kWh respectively (Figure 1; Table A-1).

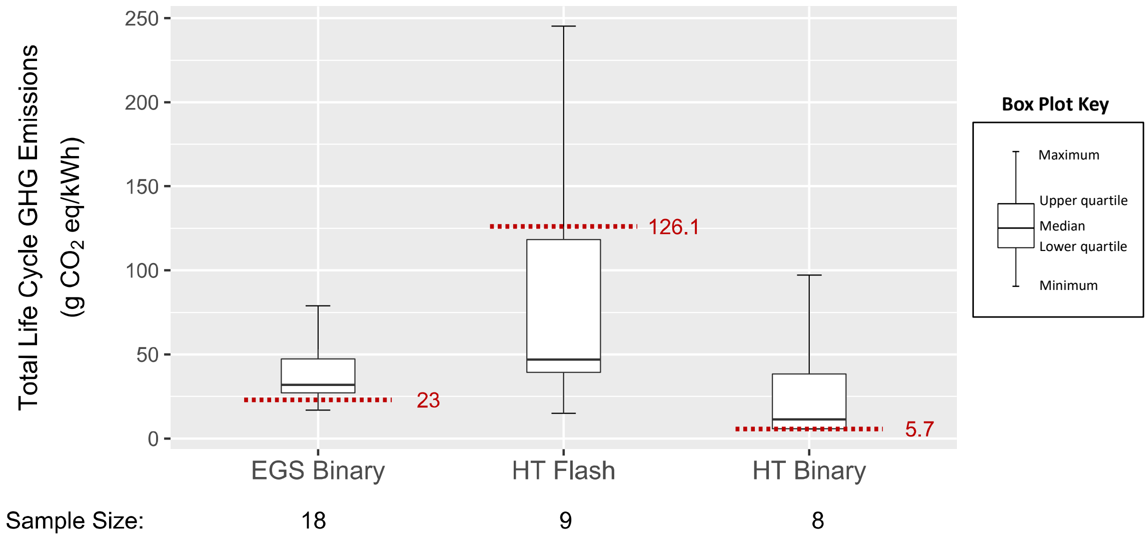

Figure 1. Side-by-side comparison of life cycle greenhouse gas (GHG) emissions from three geothermal electricity generation technologies: enhanced geothermal systems (EGS) binary, hydrothermal (HT) flash and HT binary

Estimates from Sullivan et al. (2013) are overlaid as dashed red lines with the value for each estimate reported to the right of the line. Refer to Tables A-1 and A-6 in the appendix for summary statistics and raw estimates, respectively. Sample size refers to the number of estimates forming the box plot summary statistics for each technology. (The number of studies reporting those estimates is less than or equal to the number of estimates.)

One of the studies that we analyzed (Sullivan et al. 2013) describes the sources of geothermal GHG emission estimates that are included in Argonne National Laboratory's Greenhouse gases, Regulated Emissions, and Energy use in Transportation (GREET) model, which is used by a variety of stakeholders to evaluate emission impacts of advanced vehicle and fuel technologies. As a result, we compared the results from our literature review to the data reported by Sullivan et al. (2013) (dashed lines in Figure 1 correspond to data from Sullivan et al. [2013]). While the estimates from Sullivan et al. (2013) are within the range of estimates for all three technologies explored here, they are close to the first quartile of the literature estimates for HT binary and EGS binary and the upper quartile of the literature estimates for HT flash. Thus, there is an opportunity for updates to be made to the estimates of life cycle GHG emissions within the GREET model.

GHG Emissions Disaggregated by Life Cycle Phase

Of the three geothermal electricity generation technologies examined in this report, HT flash exhibits the largest amount of variation in total life cycle GHG emissions (Figure 1). While the range for total emissions from EGS binary is 16.9–79 g CO_2 eq/kWh, the range of HT flash is 15.0–245 g CO_2 eq/kWh. When the emissions are disaggregated by phase, as in Figure 2, it is apparent that most of the variability in emissions from HT flash comes from plant operation, which is the largest contributor to the total emissions from HT flash plants. The large operational emissions from HT flash plants result from the release of non-condensable gases when the geofluid in a flash plant is exposed to the atmosphere after it passes through a turbine. Neither EGS binary systems nor HT binary systems have emissions associated with non-condensable gases because the geofluids in binary geothermal plants remain in a closed-loop system. However, the operational emissions associated with hydrothermal flash plants range widely depending on the efficiency of the plant and composition of the geofluid, which varies with location and depth.

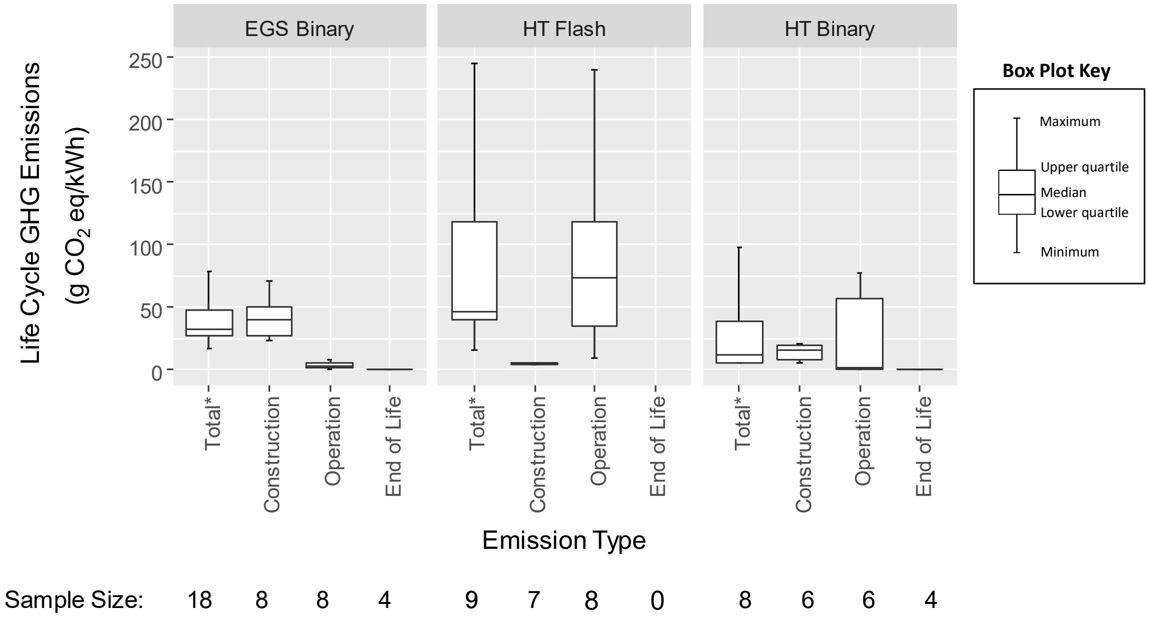

Figure 2. Greenhouse gas (GHG) emissions disaggregated by phase of the life cycle (i.e., total, construction, operation, and end of life) for three geothermal electricity generation technologies: enhanced geothermal systems (EGS) binary, hydrothermal (HT) flash, and HT binary.

Sample size refers to the number of estimates forming the box plot summary statistics for each technology. (The number of studies reporting those estimates is less than or equal to the number of estimates.)

* Several studies only report estimates of total life cycle GHG emissions (they do not disaggregate emissions by phase but they do report which life cycle phases are included in their estimates of total emissions). As a result, the sample size of total life cycle GHG emission estimates is larger than the sample size of estimates disaggregated by life cycle phase (e.g., for EGS binary, the sample size of estimates for total emissions is 18 while the sample size for construction is 8). Since per-phase emission estimates are a subset of the estimates that provide total emission estimates and the estimates of total emissions from the per-phase and total-only sources differ, the medians of the per-phase GHG emission estimates might be greater than the median of the total.

On the other hand, construction is the major contributor to total life cycle GHG emissions from EGS binary and HT binary. Because the EGS binary wells assumed in the LCA studies are two to five times deeper than HT binary wells, they require more material for construction. EGS systems also require diesel power for the hydraulic stimulation and often involve more production and injection wells (Sullivan et al. 2014). Thus, the emissions from the construction of EGS binary plants are much higher than those for HT binary plants.

Importance of Operational Emissions

Several of the geothermal LCA studies we reviewed discussed the large contribution of and the variability associated with the operational emissions from HT flash plants (Sullivan et al. 2011; Sullivan et al. 2012; Sullivan et al. 2013; Sullivan and Wang 2013; and Sullivan et al. 2014). In particular, these studies referenced a survey conducted by Bertani and Thain (2002) to assess the worldwide operational emissions from HT flash plants. From this survey, Bertani and Thain reported a weighted average of 122 grams of carbon dioxide per kilowatt hour (g CO_2/kWh) and a range of 4–740 g CO_2/kWh for operational emissions from geothermal electricity. Even without including the emissions from other types of GHGs, such as methane and nitrous oxide, the maximum amount of carbon dioxide reportedly emitted (in grams per kilowatt hour) is greater than some estimates for the total GHG emissions from natural gas power plants; the median of harmonized estimates of life cycle GHG emissions for electricity generated by a natural gas combustion turbine is 450 g CO_2 eq/kWh (O'Donoughue et al. 2014).

Many of the studies we reviewed also discuss the variability in operational emissions from flash plants in California (Sullivan et al. 2011, 2012, 2013, 2014; Sullivan and Wang 2013). For example, Sullivan et al. (2014) collected data from the California Environmental Protection Agency and found that the operational GHG emissions from HT flash plants in California had a weighted average of 103 g CO_2 eq/kWh in 2012, with 85% of the plants emitting below 170 g CO_2 eq/kWh and only two plants emitted more than 300 g CO_2 eq/kWh.

To better describe how the emissions from actual geothermal power plants compare with the GHG emissions computed from the LCA studies we reviewed, we compiled data from four studies reporting operational emissions from actual power plants: Bertani and Thain (2002), Holm et al. (2012), Sullivan and Wang (2013), and Bravi and Basosi (2014). The results of this review are illustrated in the left column of Figure 3, which shows the range of operational emissions from geothermal power plants, most of which use HT flash technology. Rather than reporting total GHG emissions, these four studies only describe emissions from one GHG, carbon dioxide because this is the only GHG for which operational emissions are reported.

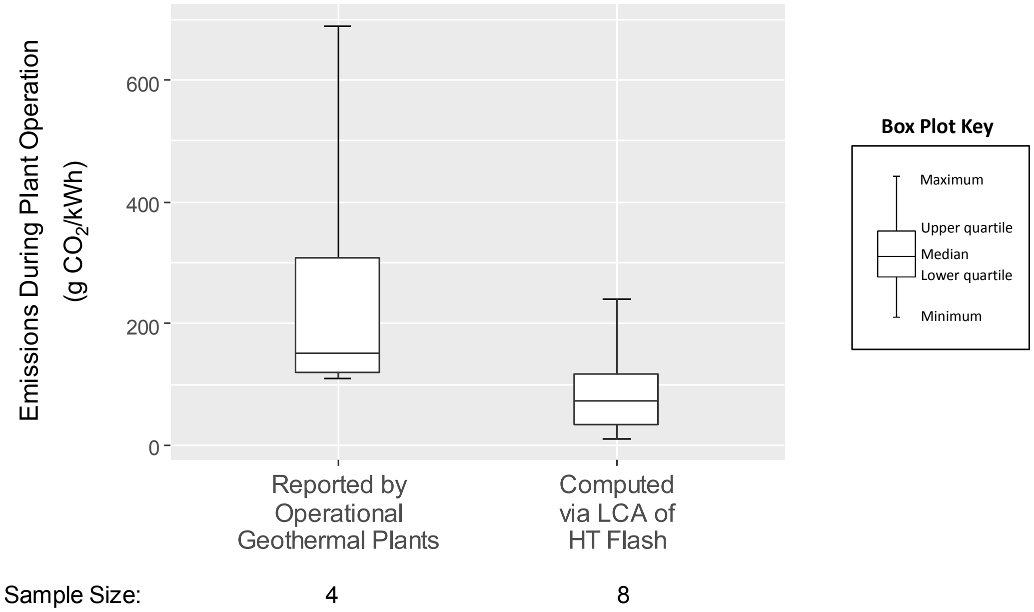

Figure 3. Comparison of carbon dioxide (CO_2) emissions reported by operational geothermal plants (compiled from Bertani and Thain 2002, Holm et al. 2012, Sullivan and Wang 2013, and Bravi and Basosi 2014) versus GHG emissions computed from life cycle assessments (LCAs) of electricity generated by hydrothermal (HT) flash plants (same values as reported in Figures 1 and 2 above).

Sample size refers to the number of estimates forming the box plot summary statistics for each technology. (The number of studies reporting those estimates is less than or equal to the number of estimates.)

It is clear from these studies that operational emissions from geothermal flash plants vary widely and may be up to ten times greater than those estimated from the LCA studies examined here. However, because the amount of non-condensable gases emitted during operation varies with multiple parameters, including geographic location, well depth, and resource temperature, and these system characteristics differ across the LCA studies and the operational studies, one would need to ensure a consistent set of system characteristics in order to perform a fair comparison of the emissions reported from operational studies and LCAs. Such a comparative analysis is beyond the scope of this work but more research needs to be done to quantify the relationships among resource location, geofluid composition, and GHG emissions. Furthermore, because most flash power plants are located in areas where natural geothermal resources (e.g., hot springs and geysers) already occur and because these areas may have a background level of GHGs from "natural" emissions, identifying the emissions of anthropogenic geothermal systems could be difficult. Thus, more work also needs to be done to identify the difference between natural and geothermal electricity-induced GHG emissions.

Conclusions

We performed a systematic review of the LCA literature on geothermal energy, evaluating the quality, completeness, transparency, and relevance of over 180 geothermal environmental impact studies. We identified 29 LCA studies on geothermal energy that passed our rigorous screening methodology. These studies included assessments for the GHG emissions and water use associated with geothermal electricity generation, heat generation, and combined heat and power. We then examined three electricity generation technologies (i.e., EGS binary, HT binary, and HT flash) in detail and compiled published estimates for life cycle GHG emissions.

There are several limitations of this work. First, we only examine the GHG emissions associated with three geothermal technologies that generate electricity. There are other types of geothermal technologies, including those that produce heat for heating purposes, that could be addressed in future research. Second, the results presented here only represent an examination of one environmental impact category: climate change (as measured by life cycle GHG emissions). Numerous other impact categories, such human toxicity, land use, and resource consumption would need to be examined to gain a more comprehensive understanding of the life cycle environmental impacts of geothermal electricity. Third, the results presented here do not represent the distribution of likelihood for actual life cycle GHG emissions from geothermal electricity. As evidenced by the comparison of operational emissions, the results compiled from these LCAs may not represent all possible variations in parameters associated with geothermal energy. Finally, the results presented here are published estimates, not adjusted for consistency in methods or underlying assumptions, as has been completed for many other generation technologies in NREL's LCA Harmonization Project. There are several inconsistencies among the estimates that we compiled for life cycle GHG emissions. For example, these studies comprise a wide variety of geographic regions, well depths, and temperatures; they also use different impact assessment methods, characterization factors, operating lifetimes, and system boundaries. A complete harmonization of these studies would provide a more consistent estimate of central tendency for life cycle GHG emissions of these geothermal generation technologies.

Despite these limitations, our analysis revealed that, of the three geothermal electricity generation technologies considered, HT flash generates the most GHG emissions per kilowatt hour of electricity (median of 47 g CO_2 eq/kWh). These median GHG emissions from HT flash were nearly 50% greater than the median for EGS binary and over four times greater than median for HT binary. Furthermore, while most of the GHG emissions from HT binary and EGS binary are associated with the construction of these technologies, GHG emissions from HT flash primarily result from operation of the facility. These operational emissions result from the open-loop nature of HT flash technology, which releases non-condensable gases when the geofluid is exposed to the atmosphere.

The variability in operational GHG emissions from geothermal power plants presents a challenging problem for computing the technology's impact on climate change. We show that the median CO_2 emissions reported by operational geothermal plants are approximately two times larger than the median LCA estimates of GHG emissions from the operation of HT flash plants. Because the operational emissions of geothermal plants vary widely with system characteristics (e.g., local geology, depth, temperature), the differences in operational emissions reported by LCAs and operational studies are likely a result of differences in the system characteristics that are used in these studies. A better understanding of the distribution of non-condensable gases in geothermal reservoirs, as well as the effects of reservoir depletion and repressurization on GHG emissions profiles over time, would improve estimates of life cycle GHG emissions from geothermal plants.

Overall, we show that there are large variations in the life cycle GHG emissions from three types of geothermal technologies that generate electricity: HT flash, HT binary, and EGS binary. The median estimates for HT binary and EGS binary technologies generate less than 40 g CO_2 eq/kWh, which represents the same order as most other renewable energy technologies (IPCC 2011). However, the median value in the literature for HT flash is slightly higher (47 g CO_2 eq/kWh), and the range of literature and operational emissions from this technology indicate it may generate three to ten times more GHG emissions than other renewable energy technologies. Because EGSs are still in the development and demonstration phase, the estimate for GHG emissions from EGS binary might change once the technology is commercialized. On the other hand, HT binary is a more mature technology than EGS binary and appears to have the lowest life cycle GHG emissions of the three types of geothermal electricity generation technologies examined here.

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Appendix. Supplementary Material

Table A-1. Total Life Cycle GHG Emissions from Three Types of Geothermal Electricity: EGS Binary, HT Binary, and HT Flash[a]

	EGS Binary	HT Flash	HT Binary	All Technologies
Min (g CO_2 eq/kWh)	16.9	15.0	5.6	5.6
Quartile 1 (g CO_2 eq/kWh)	27.2	39.4	5.8	21.9
Median (g CO_2 eq/kWh)	32.0	47.0	11.3	36.7
Quartile 3 (g CO_2 eq/kWh)	47.5	118.4	38.5	51.5
Max (g CO_2 eq/kWh)	79.0	245.2	97.2	245.2
Sample size	18	9	8	35

a) These values were computed from the estimates obtained from the studies that passed both of our literature screens. EGS Binary = enhanced geothermal systems used in the operation of binary cycle power plants, HT binary = hydrothermal (HT) resources used in binary cycle plants, and HT flash = high temperature HT resources that are vaporized in flash steam plants.

Table A-2. GHG Emissions from the Construction Phase of Three Types of Geothermal Electricity: EGS Binary, HT Binary, and HT Flash[a]

	EGS Binary	HT Flash	HT Binary	All Technologies
Min (g CO_2 eq/kWh)	23.0	3.9	5.7	3.9
Quartile 1 (g CO_2 eq/kWh)	27.7	4.1	8.0	5.2
Median (g CO_2 eq/kWh)	39.9	5.0	15.0	15.3
Quartile 3 (g CO_2 eq/kWh)	50.2	5.1	19.1	27.7
Max (g CO_2 eq/kWh)	71.1	5.3	20.5	71.1
Sample size	8	7	6	21

a) These values were computed from the estimates obtained from the studies that passed both of our literature screens. EGS Binary = enhanced geothermal systems used in the operation of binary cycle power plants, HT binary = hydrothermal (HT) resources used in binary cycle plants, and HT flash = high temperature HT resources that are vaporized in flash steam plants.

Table A-3 GHG Emissions from the Operation Phase of Three Types of Geothermal Electricity: EGS Binary, HT Binary, and HT Flash[a]

	EGS Binary	HT Flash	HT Binary	All Technologies
Min (g CO_2 eq/kWh)	0.0	9.7	0.0	0.0
Quartile 1 (g CO_2 eq/kWh)	1.0	34.6	0.7	1.0
Median (g CO_2 eq/kWh)	2.5	73.2	0.9	6.9
Quartile 3 (g CO_2 eq/kWh)	5.4	118.3	56.1	58.1
Max (g CO_2 eq/kWh)	7.5	240.2	76.8	240.2
Sample size	8	8	7	23

a) These values were computed from the estimates obtained from the studies that passed both of our literature screens. EGS Binary = enhanced geothermal systems used in the operation of binary cycle power plants, HT binary = hydrothermal (HT) resources used in binary cycle plants, and HT flash = high temperature HT resources that are vaporized in flash steam plants.

Table A-4. GHG Emissions from the End of Life Phase of Three Types of Geothermal Electricity: EGS Binary, HT Binary, and HT Flash[a]

	EGS Binary	HT Flash	HT Binary	All Technologies
Min (g CO_2 eq/kWh)	0.15	-	0.04	0.04
Quartile 1 (g CO_2 eq/kWh)	0.16	-	0.04	0.07
Median (g CO_2 eq/kWh)	0.21	-	0.06	0.12
Quartile 3 (g CO_2 eq/kWh)	0.29	-	0.08	0.18
Max (g CO_2 eq/kWh)	0.40	-	0.08	0.40
Sample size	4	-	4	8

a) These values were computed from the estimates obtained from the studies that passed both of our literature screens. EGS Binary = enhanced geothermal systems used in the operation of binary cycle power plants, HT binary = hydrothermal (HT) resources used in binary cycle plants, and HT flash = high temperature HT resources that are vaporized in flash steam plants.

Table A-5. CO_2 Emissions from the Operation Phase of Active Geothermal Plants Compared to GHG Emissions Computed via LCA of HT Flash Technology[a]

	CO_2 Emissions Reported by Operational Plants	GHG Emissions Computed via LCA of HT Flash
Min (g CO_2 eq/kWh)	110.0	9.7
Quartile 1 (g CO_2 eq/kWh)	119.0	34.6
Median (g CO_2 eq/kWh)	151.0	73.2
Quartile 3 (g CO_2 eq/kWh)	307.6	118.3
Max (g CO_2 eq/kWh)	690.2	240.2
Sample size	4	8

a) Emissions from operational plants were compiled from Bertani and Thain (2002), Holm et al. (2012), Sullivan and Wang (2013), and Bravi and Basosi (2014). GHG emissions computed via LCA were obtained from the studies that passed both of our literature screens (see Column 3 of Table A-3). The data in Table A-5 were used to generate Figure 3.

Table A-6. Life Cycle GHG Estimates from the 29 Studies that Passed both Rounds of Screening

Author(s)	Year	Technology	Emissions (g CO_2eq / kWh)			
			Total	Constr.	Oper.	EOL
Rule et al.	2009	HT binary	5.6	-	-	-
Sullivan et al.	2013	HT binary	5.7	5.7	0	-
Martin-Gamboa et al.	2015	HT binary	5.79	-	-	-
Sullivan et al.	2014	HT binary	6.4	5.7	0.72	-
Heberle et al.	2016	HT binary	89.2	14.7	74.4	0.04
Heberle et al.	2016	HT binary	16.1	15.3	0.8	0.04
Heberle et al.	2016	HT binary	97.2	20.3	76.8	0.08
Heberle et al.	2016	HT binary	21.6	20.5	1	0.08
Lacirignola and Blanc	2013	EGS binary	16.9	-	-	-
Lacirignola and Blanc	2013	EGS binary	21.8	-	-	-
Lacirignola and Blanc	2013	EGS binary	22	-	-	-
Treyer et al.	2014	EGS binary	24	23	1	-
Bauer et al.	2008	EGS binary	27	-	-	-
Sullivan et al.	2013	EGS binary	27.7	27.7	0	-
Lacirignola and Blanc	2013	EGS binary	28.6	-	-	-
Lacirignola and Blanc	2013	EGS binary	29.2	-	-	-
Lacirignola and Blanc	2013	EGS binary	29.3	-	-	-
Sullivan et al.	2014	EGS binary	34.6	27.7	6.89	-
Lacirignola and Blanc	2013	EGS binary	36.7	33.03	3.67	-
Lacirignola and Blanc	2013	EGS binary	37.9	-	-	-
Lacirignola and Blanc	2013	EGS binary	40.4	-	-	-
Lacirignola and Blanc	2013	EGS binary	49.8	-	-	-
Frick et al.	2010	EGS binary	51	49.827	1.02	0.153
Rogge and Kaltschmitt	2003	EGS binary	52	46.8	4.94	0.26
Frick et al.	2010	EGS binary	53	51.516	1.325	0.159
Rogge and Kaltschmitt	2003	EGS binary	79	71.1	7.505	0.395
Karlsdottir et al.	2010a	HT flash	40	-	-	-
Hondo	2005	HT flash	15	5.3	9.7	-
Sullivan et al.	2014	HT flash	109	4.1	104.51	-
Sullivan et al.	2013	HT flash	126.1	4.1	122	-
Skone et al.	2012	HT flash	245.2	5	240.2	-
Marchand et al.	2015	HT flash	47	5.17	41.83	-
Marchand et al.	2015	HT flash	38.5	3.85	34.65	-
Marchand et al.	2015	HT flash	39.4	5.122	34.278	-
Martínez-Corona et al.	2017	HT flash	118.35	-	117	-

Table A-7. Studies Screened, with Results for Each Screening Criterion

"Y" (yes) indicates that the source met the requirement, while "N" (no) means it did not pass. A "−" indicates that the criterion was not applicable for that study. A "Y" in column P1 (P2) indicates that the study passed the first (second) screen. The table is sorted first on whether the sources passed the first screen, then whether they passed the second screen, then alphabetically. A description of each screening column is presented in Table A-8.

Literature		First Screen								Second Screen											
Author(s)	Year	A	B	C	D	E	F	G	P1	H	I	J	K	L	M	N	O	P	Q	R	P2
Bauer et al.	2008	Y	Y	Y	Y	Y	Y	−	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Buonocore et al.	2015	Y	Y	Y	Y	Y	Y	−	Y	Y	Y	−	Y	Y	Y	−	Y	Y	Y	Y	Y
Clark et al.	2013	Y	Y	Y	Y	Y	Y	−	Y	Y	Y	Y	Y	Y	Y	−	Y	Y	Y	Y	Y
Clark et al.	2011a	Y	Y	Y	Y	Y	Y	−	Y	Y	Y	Y	Y	Y	Y	−	Y	Y	Y	Y	Y
Frick et al.	2010	Y	Y	Y	Y	Y	Y	−	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Genchi et al.	2002	Y	Y	Y	Y	Y	Y	−	Y	Y	Y	Y	Y	Y	Y	−	Y	Y	Y	Y	Y
Ghafghazi et al.	2011	Y	Y	Y	Y	Y	Y	−	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Gilli et al.	1999	Y	Y	Y	Y	Y	Y	−	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Heberle et al	2016	Y	Y	Y	Y	Y	Y	−	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Hondo	2005	Y	Y	Y	Y	Y	Y	−	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Karlsdottir et al.	2010a	Y	Y	Y	Y	Y	Y	−	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Karlsdottir et al.	2010b	Y	Y	Y	Y	Y	Y	−	Y	Y	Y	Y	Y	Y	Y	−	Y	Y	Y	Y	Y
Kim et al.	2015	Y	Y	Y	Y	Y	Y	−	Y	Y	Y	−	Y	Y	Y	Y	Y	Y	Y	Y	Y
Lacirignola and Blanc	2013	Y	Y	Y	Y	Y	Y	−	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Marchand et al.	2015	Y	Y	Y	Y	Y	Y	−	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Martínez-Corona et al.	2017	Y	Y	Y	Y	Y	Y	−	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Martin-Gamboa et al.	2015	Y	Y	Y	Y	Y	Y	−	Y	Y	Y	−	Y	Y	Y	Y	Y	Y	Y	Y	Y
Mattinen et al.	2015	Y	Y	Y	Y	Y	Y	−	Y	Y	Y	−	Y	Y	Y	−	Y	Y	Y	Y	Y
et al.	2013	Y	Y	Y	Y	Y	Y	−	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Ristimäki et al.	2013	Y	Y	Y	Y	Y	Y	−	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Rogge and Kaltschmitt	2003	Y	Y	Y	Y	Y	Y	−	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Rule et al.	2009	Y	Y	Y	Y	Y	Y	−	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Russo et al.	2014	Y	Y	Y	Y	Y	Y	−	Y	Y	Y	Y	Y	Y	Y	−	Y	Y	Y	Y	Y
Ruzzenenti et al.	2014	Y	Y	Y	Y	Y	Y	−	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Saner et al.	2010	Y	Y	Y	Y	Y	Y	−	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Skone et al.	2012	Y	Y	Y	Y	Y	Y	−	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Sullivan et al.	2014	Y	Y	Y	Y	Y	Y	−	Y	Y	Y	Y	Y	Y	Y	−	Y	Y	Y	Y	Y
Sullivan et al.	2013	Y	Y	Y	Y	Y	Y	−	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y

Literature		First Screen								Second Screen											
Author(s)	Year	A	B	C	D	E	F	G	P1	H	I	J	K	L	M	N	O	P	Q	R	P2
Treyer et al.	2014	Y	Y	Y	Y	Y	Y	–	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Abusoglu and Sedeeq	2013	Y	Y	Y	Y	Y	Y	–	Y	Y	Y	–	Y	Y	Y	Y	Y	Y	N	Y	N
Amponsah et al.	2014	Y	Y	Y	Y	Y	Y	–	Y	N	N	–	–	–	–	–	–	–	–	–	N
Asdrubali et al.	2015	Y	Y	Y	Y	Y	Y	–	Y	Y	Y	–	Y	Y	N	–	–	–	–	–	N
Bauer et al.	2010	Y	Y	Y	Y	Y	Y	–	Y	Y	Y	–	–	–	–	–	–	–	N	–	N
Benke and Patzay	2010	Y	Y	Y	Y	Y	Y	–	Y	Y	Y	–	Y	Y	Y	Y	Y	Y	N	Y	N
Bonamente et al.	2015	Y	Y	Y	Y	Y	Y	–	Y	Y	Y	Y	N	Y	Y	Y	Y	Y	Y	N	N
Bravi and Basosi	2014	Y	Y	Y	Y	Y	Y	–	Y	N	Y	–	Y	Y	Y	–	Y	Y	Y	Y	N
Brown and Ulgiati	2002	Y	Y	Y	Y	Y	Y	–	Y	N	–	–	–	–	–	–	–	–	–	–	N
Clark and Harto	2012	Y	Y	Y	Y	Y	Y	–	Y	Y	Y	Y	Y	Y	N	–	–	–	–	–	N
Clark, Harto, and Troppe	2011	Y	Y	Y	Y	Y	Y	–	Y	Y	Y	–	Y	Y	Y	–	Y	Y	Y	N	N
Evans and Strezov	2010	Y	Y	Y	Y	Y	Y	–	Y	N	N	–	–	–	N	–	–	–	–	–	N
Evans et al.	2009	Y	Y	Y	Y	Y	Y	–	Y	N	N	–	–	–	–	–	–	–	–	–	N
Frank et al.	2012	Y	Y	Y	Y	Y	Y	–	Y	Y	Y	–	Y	Y	Y	Y	Y	Y	Y	N	N
Frick et al.	2007	Y	Y	Y	Y	Y	Y	–	Y	Y	Y	–	N	Y	Y	Y	Y	N	Y	Y	N
Fthenakis and Kim	2010	Y	Y	Y	Y	Y	Y	–	Y	N	N	–	–	–	N	–	–	–	–	–	N
Gerber and Marechal	2012	Y	Y	Y	Y	Y	Y	–	Y	Y	Y	Y	Y	Y	Y	Y	Y	N	Y	Y	N
Huang and Mauerhofer	2015	Y	Y	Y	Y	Y	Y	–	Y	N	–	–	–	–	–	–	–	–	–	–	N
IEA	1998	Y	Y	Y	Y	Y	Y	–	Y	Y	Y	–	Y	Y	Y	–	N	Y	Y	Y	N
Jacobson	2009	Y	Y	Y	Y	Y	Y	–	Y	N	N	–	–	–	–	–	–	–	–	–	N
Karlsdottir et al.	2015	Y	Y	Y	Y	Y	Y	–	Y	Y	N	–	Y	Y	Y	–	Y	Y	Y	Y	N
Kayser and Kaltschmitt	1997a	Y	Y	Y	Y	Y	Y	–	Y	Y	N	–	N	N	Y	N	Y	Y	Y	Y	N
Kenny et al.	2010	Y	Y	Y	Y	Y	Y	–	Y	N	N	–	–	–	N	–	–	–	–	–	N
Kim and Fthenakis	2008	Y	Y	Y	Y	Y	Y	–	Y	Y	–	–	–	–	N	–	–	–	–	–	N
Koroneos	2007	Y	Y	Y	Y	Y	Y	–	Y	Y	Y	–	Y	Y	N	–	Y	Y	Y	Y	N
Lacirignola et al.	2017	Y	Y	Y	Y	Y	Y	–	Y	Y	Y	Y	Y	Y	Y	Y	Y	N	N	Y	N
Macknick et al.	2012	Y	Y	Y	Y	Y	Y	–	Y	N	Y	–	Y	Y	N	–	N	Y	Y	Y	N
Martin	1997	Y	Y	Y	Y	Y	Y	–	Y	Y	Y	–	Y	Y	Y	Y	N	Y	Y	Y	N
Matuszewska	2011	Y	Y	Y	Y	Y	Y	–	Y	Y	Y	Y	Y	Y	Y	Y	Y	N	Y	Y	N
Nitkiewicz and Sekret	2014	Y	Y	Y	Y	Y	Y	–	Y	Y	N	–	Y	Y	Y	Y	Y	Y	N	Y	N
Pehnt	2006	Y	Y	Y	Y	Y	Y	–	Y	Y	Y	–	Y	Y	Y	Y	N	Y	Y	Y	N
Rodriguez et al.	2012	Y	Y	Y	Y	Y	Y	–	Y	Y	Y	–	N	N	Y	N	Y	Y	Y	Y	N

Literature		First Screen								Second Screen											
Author(s)	Year	A	B	C	D	E	F	G	P1	H	I	J	K	L	M	N	O	P	Q	R	P2
San Martin	1989	Y	Y	Y	Y	Y	Y	–	Y	N	N	–	–	–	–	–	–	–	–	–	N
Santoyo-Castelazo et al.	2011	Y	Y	Y	Y	Y	Y	–	Y	Y	Y	–	N	Y	Y	Y	Y	N	Y	Y	N
Schroeder, Harto, et al.	2014	Y	Y	Y	Y	Y	Y	–	Y	N	Y	–	N	–	–	–	–	–	–	–	N
Schroeder, Clark, and Harto	2014	Y	Y	Y	Y	Y	Y	–	Y	N	–	–	–	–	–	–	–	–	–	–	N
Sovacool	2008	Y	Y	Y	Y	Y	Y	–	Y	Y	Y	Y	Y	Y	N	–	–	–	–	–	N
Sullivan et al.	2011	Y	Y	Y	Y	Y	Y	–	Y	Y	Y	Y	Y	Y	Y	–	Y	Y	Y	N	N
Sullivan et al.	2012	Y	Y	Y	Y	Y	Y	–	Y	Y	Y	Y	Y	Y	N	–	Y	Y	Y	Y	N
Sullivan et al.	2010	Y	Y	Y	Y	Y	Y	–	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	N
Sullivan and Wang	2013a	Y	Y	Y	Y	Y	Y	–	Y	N	Y	–	Y	Y	N	Y	Y	Y	Y	Y	N
Sullivan and Wang	2013b	Y	Y	Y	Y	Y	Y	–	Y	Y	Y	–	Y	Y	N	N	N	N	Y	Y	N
Tolba and ElMahgary	1985	Y	Y	Y	Y	Y	Y	–	Y	N	Y	–	N	Y	Y	–	Y	Y	Y	Y	N
Treyer and Bauer	2010	Y	Y	Y	Y	Y	Y	–	Y	Y	Y	–	N	–	–	–	–	–	–	–	N
Uchiyama	1997	Y	Y	Y	Y	Y	Y	–	Y	N	N	–	N	N	Y	–	Y	Y	Y	Y	N
Uchiyama	2007	Y	Y	Y	Y	Y	Y	–	Y	Y	N	–	N	N	–	–	–	–	–	–	N
Chiavetta et al.	2011	Y	Y	Y	Y	Y	Y	–	Y	Y	Y	–	N	–	–	–	–	–	–	–	–
Clark and Harto	2013	Y	Y	Y	Y	Y	Y	–	Y	Y	Y	–	N	–	–	–	–	–	–	–	–
Gudikson	1989	Y	Y	Y	Y	Y	N	–	N	N	N	–	–	–	–	–	–	–	–	–	N
Guo et al.	2013	Y	Y	Y	Y	Y	Y	–	Y	Y	Y	–	Y	N	–	–	–	–	–	–	–
Haddad and Dones	1991	Y	Y	Y	Y	Y	N	–	N	N	N	–	–	–	–	–	–	–	–	–	N
Herendeen and Plant	1981	Y	Y	Y	Y	Y	N	–	N	N	N	–	Y	Y	Y	–	Y	N	Y	Y	N
Hienuki et al.	2015	Y	Y	Y	Y	Y	Y	–	Y	N	–	–	–	–	–	–	–	–	–	–	–
Kammen and Pacca	2004	Y	Y	Y	Y	Y	Y	–	Y	N	–	–	–	–	–	–	–	–	–	–	–
Adee and Moore	2010	Y	Y	N	–	–	–	–	N	–	–	–	–	–	–	–	–	–	–	–	–
Akai et al.	1997	Y	Y	Y	Y	N	–	–	N	–	–	–	–	–	–	–	–	–	–	–	–
Armannsson et al.	2005	Y	Y	Y	Y	Y	N	–	N		–	–	–	–	–	–	–	–	–	–	–
Arslan	2010	Y	Y	Y	Y	Y	N	–	N	–	–	–	–	–	–	–	–	–	–	–	–
Azim et al.	2010	Y	Y	N	–	–	–	–	N	–	–	–	–	–	–	–	–	–	–	–	–
Barbier	2002	Y	Y	Y	Y	Y	N	–	N	–	–	–	–	–	–	–	–	–	–	–	–
Barfield	2006	Y	Y	Y	Y	Y	N	–	N	–	–	–	–	–	–	–	–	–	–	–	–
Bayer et al.	2013	Y	Y	Y	Y	Y	N	–	N	–	–	–	–	–	–	–	–	–	–	–	–
Bayer et al.	2012	Y	Y	Y	Y	Y	N	–	N	–	–	–	–	–	–	–	–	–	–	–	–
Bertani and Thain	2002	Y	Y	N	Y	Y	N	–	N	–	–	–	–	–	–	–	–	–	–	–	–

Literature		First Screen								Second Screen											
Author(s)	Year	A	B	C	D	E	F	G	P1	H	I	J	K	L	M	N	O	P	Q	R	P2
Bloomfield and Moore	1999	Y	Y	Y	Y	Y	N	–	N		–	–	–	–	–	–	–	–	–	–	–
Bloomfield et al.	2003	Y	Y	N	Y	Y	N	–	N	–	–	–	–	–	–	–	–	–	–	–	–
Booth and Neil	1998	Y	Y	N	–	–	–	–	N	–	–	–	–	–	–	–	–	–	–	–	–
Boran	2013	Y	Y	Y	Y	Y	N	–	N	–	–	–	–	–	–	–	–	–	–	–	–
Brophy	1997	Y	Y	Y	Y	Y	N	–	N	–	–	–	–	–	–	–	–	–	–	–	–
Brugman et al.	1995	Y	Y	Y	Y	Y	N	–	N	–	–	–	–	–	–	–	–	–	–	–	–
Canelli et al.	2015	Y	Y	Y	Y	Y	N	–	N	–	–	–	–	–	–	–	–	–	–	–	–
Carvalho et al.	2015	Y	Y	Y	Y	Y	N	–	N	–	–	–	–	–	–	–	–	–	–	–	–
Chamorro et al.	2012	Y	Y	Y	Y	Y	N	–	N	–	–	–	–	–	–	–	–	–	–	–	–
Clark et al.	2009	Y	Y	Y	Y	Y	N	–	N	–	–	–	–	–	–	–	–	–	–	–	–
Clark et al.	2011b	Y	N	Y	Y	Y	N	–	N	–	–	–	–	–	–	–	–	–	–	–	–
Clark et al.	2014	Y	Y	Y	Y	Y	N	–	N	–	–	–	–	–	–	–	–	–	–	–	–
DiPippo	1988	Y	Y	N	–	–	–	–	N	–	–	–	–	–	–	–	–	–	–	–	–
DiPippo	2008	Y	Y	Y	Y	Y	N	–	N		–	–	–	–	–	–	–	–	–	–	–
Dones et al.	2007	Y	Y	Y	Y	N	Y	–	N		–	–	–	–	–	–	–	–	–	–	–
Dones et al.	1999	Y	N	Y	Y	N	–	–	N	–	–	–	–	–	–	–	–	–	–	–	–
Dones et al.	2005	Y	Y	Y	Y	N	–	–	N	–	–	–	–	–	–	–	–	–	–	–	–
Dotzauer	2010	Y	Y	Y	Y	Y	N	–	N	–	–	–	–	–	–	–	–	–	–	–	–
Eggertson	2004	Y	Y	N	–	–	–	–	N	–	–	–	–	–	–	–	–	–	–	–	–
Ekrami and Sadeghi	2009	Y	N	Y	N	–	–	–	N	–	–	–	–	–	–	–	–	–	–	–	–
El-Emam and Dincer	2013	Y	Y	Y	Y	Y	N	–	N	–	–	–	–	–	–	–	–	–	–	–	–
Falcone and Borggard	1991	Y	Y	N	Y	Y	N	–	N	–	–	–	–	–	–	–	–	–	–	–	–
Feck and Wagner	2008	Y	Y	Y	N	Y	Y	–	N	–	–	–	–	–	–	–	–	–	–	–	–
Frick and Kaltschmitt	2009	Y	N	Y	N	–	–	–	N	–	–	–	–	–	–	–	–	–	–	–	–
Frischknecht et al.	2009	Y	Y	Y	Y	N	N	–	N	–	–	–	–	–	–	–	–	–	–	–	–
Gagnon et al.	2002	Y	Y	Y	Y	N	Y	–	N	–	–	–	–	–	–	–	–	–	–	–	–
Ganjehsarabi et al.	2012	Y	Y	Y	Y	Y	N	–	N	–	–	–	–	–	–	–	–	–	–	–	–
Geothermal Technologies Office	2008	Y	Y	Y	Y	Y	N	–	N	–	–	–	–	–	–	–	–	–	–	–	–
Hadian and Madani	2015	Y	Y	Y	Y	Y	N	–	N		–	–	–	–	–	–	–	–	–	–	–
Hamamatsu	2003	Y	Y	Y	N	–	–	–	N	–	–	–	–	–	–	–	–	–	–	–	–
Hamamatsu et al.	2004	Y	Y	Y	Y	Y	N	–	N	–	–	–	–	–	–	–	–	–	–	–	–
Hammons	2007	Y	Y	Y	Y	Y	N	–	N		–	–	–	–	–	–	–	–	–	–	–

Literature		First Screen								Second Screen											
Author(s)	Year	A	B	C	D	E	F	G	P1	H	I	J	K	L	M	N	O	P	Q	R	P2
Harto and Clark	2012	Y	Y	Y	Y	Y	N	–	N	–	–	–	–	–	–	–	–	–	–	–	–
Harto et al.	2014	Y	Y	Y	Y	Y	N	–	N	–	–	–	–	–	–	–	–	–	–	–	–
Holm et al.	2012	Y	Y	Y	Y	Y	N	–	N		–	–	–	–	–	–	–	–	–	–	–
Hunt	2001	Y	Y	Y	Y	Y	N	–	N	–	–	–	–	–	–	–	–	–	–	–	–
Inhaber	2004	Y	Y	Y	Y	Y	N	–	N	–	–	–	–	–	–	–	–	–	–	–	–
Iwaoka et al.	2008	Y	N	Y	N	Y	Y	–	N	–	–	–	–	–	–	–	–	–	–	–	–
Jensen	2007	Y	N	Y	N	Y	–	–	N	–	–	–	–	–	–	–	–	–	–	–	–
Joblin	2005	Y	Y	Y	Y	Y	N	–	N	–	–	–	–	–	–	–	–	–	–	–	–
Kabassi and Cho	2012	Y	N	Y	Y	N	–	–	N	–	–	–	–	–	–	–	–	–	–	–	–
Kagel	2008	Y	Y	Y	Y	Y	N	–	N	–	–	–	–	–	–	–	–	–	–	–	–
Kagel and Gawell	2005	Y	Y	Y	Y	Y	N	–	N	–	–	–	–	–	–	–	–	–	–	–	–
Kagel et al.	2007	Y	Y	Y	Y	Y	N	–	N	–	–	–	–	–	–	–	–	–	–	–	–
Kayser and Kaltschmitt	1997b	Y	Y	Y	N	–	–	–	N	–	–	–	–	–	–	–	–	–	–	–	–
Kim et al.	2013	Y	Y	Y	Y	Y	N	–	N	–	–	–	–	–	–	–	–	–	–	–	–
Klein and Whalley	2015	Y	Y	Y	Y	Y	N	–	N	–	–	–	–	–	–	–	–	–	–	–	–
Koroneos and Roumbas	2012	Y	Y	Y	Y	Y	N	–	N	–	–	–	–	–	–	–	–	–	–	–	–
Koroneos and Tsarouhis	2012	Y	Y	Y	Y	N	Y	–	N	–	–	–	–	–	–	–	–	–	–	–	–
Kummert et al.	2006	Y	Y	Y	Y	Y	N	–	N	–	–	–	–	–	–	–	–	–	–	–	–
Kutscher and Costenaro	2002	Y	Y	Y	Y	Y	N	–	N	–	–	–	–	–	–	–	–	–	–	–	–
Lacirignola et al.	2014	Y	Y	Y	Y	Y	N	–	N		–	–	–	–	–	–	–	–	–	–	–
Layton and Pimentel	1980	Y	Y	Y	Y	Y	N	–	N	–	–	–	–	–	–	–	–	–	–	–	–
Levi et al.	2003	Y	Y	Y	Y	Y	N	–	N	–	–	–	–	–	–	–	–	–	–	–	–
Liu et al.	2008	Y	Y	N	Y	Y	Y	–	N	–	–	–	–	–	–	–	–	–	–	–	–
Lovekin	1988	Y	Y	Y	Y	Y	N	–	N	–	–	–	–	–	–	–	–	–	–	–	–
Lux and Kaltschmitt	1997	Y	Y	Y	N	–	–	–	N	–	–	–	–	–	–	–	–	–	–	–	–
Macknick et al.	2011	Y	Y	Y	Y	Y	N	–	N		–	–	–	–	–	–	–	–	–	–	–
Mahon et al.	1980	Y	Y	Y	Y	Y	N	–	N	–	–	–	–	–	–	–	–	–	–	–	–
Mansure	2011	Y	Y	N	Y	–	–	–	N	–	–	–	–	–	–	–	–	–	–	–	–
Mason et al.	2010	Y	Y	Y	Y	Y	N	–	N	–	–	–	–	–	–	–	–	–	–	–	–
McCulloch et al.	2003	Y	Y	Y	Y	Y	N	–	N	–	–	–	–	–	–	–	–	–	–	–	–
McFarlane et al	2012	Y	Y	Y	Y	Y	N	–	N	–	–	–	–	–	–	–	–	–	–	–	–
Menberg et al.	2016	Y	Y	Y	Y	Y	N	–	N	–	–	–	–	–	–	–	–	–	–	–	–

Literature		First Screen								Second Screen											
Author(s)	**Year**	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**P1**	**H**	**I**	**J**	**K**	**L**	**M**	**N**	**O**	**P**	**Q**	**R**	**P2**
Miller	1996	Y	Y	N	Y	Y	N	–	N	–	–	–	–	–	–	–	–	–	–	–	–
Mirasgedis and Diakouaki	1997	Y	Y	Y	Y	N	N	–	N	–	–	–	–	–	–	–	–	–	–	–	–
Mohan et al.	2015	Y	Y	Y	Y	Y	N	–	N		–	–	–	–	–	–	–	–	–	–	–
Morrissey et al.	2004	Y	Y	Y	Y	N	–	–	N	–	–	–	–	–	–	–	–	–	–	–	–
Nill, M.	2004	Y	N	Y	N	–	–	–	N	–	–	–	–	–	–	–	–	–	–	–	–
Onat and Bayar	2010	Y	Y	Y	Y	Y	N	–	N	–	–	–	–	–	–	–	–	–	–	–	–
Pfister et al.	2011	Y	Y	Y	Y	Y	N	–	N	–	–	–	–	–	–	–	–	–	–	–	–
Rentizelas and Georgakellos	2014	Y	Y	Y	Y	Y	N	–	N	–	–	–	–	–	–	–	–	–	–	–	–
Rice	1980	Y	Y	Y	Y	Y	N	–	N	–	–	–	–	–	–	–	–	–	–	–	–
Roth and Ambs	2004	Y	Y	Y	Y	N	N	–	N	–	–	–	–	–	–	–	–	–	–	–	–
Sabonnadiere et al.	2007	Y	N	Y	N	Y	–	–	N	–	–	–	–	–	–	–	–	–	–	–	–
Sakurai et al.	2011	Y	Y	Y	Y	Y	N	–	N		–	–	–	–	–	–	–	–	–	–	–
Saner et al.	2014	Y	Y	Y	Y	Y	N	–	N		–	–	–	–	–	–	–	–	–	–	–
Schroeder et al.	2013	Y	Y	Y	Y	Y	N	–	N	–	–	–	–	–	–	–	–	–	–	–	–
Sivasakthivel et al.	2015	Y	Y	Y	Y	Y	N	–	N	–	–	–	–	–	–	–	–	–	–	–	–
Sovacool	2010	Y	Y	Y	Y	Y	N	–	N	–	–	–	–	–	–	–	–	–	–	–	–
Tomasini-Montenegro et al.	2016	Y	Y	Y	Y	Y	N	–	N	–	–	–	–	–	–	–	–	–	–	–	–
Twidell and Weir	1986	Y	Y	Y	Y	Y	N	–	N	–	–	–	–	–	–	–	–	–	–	–	–
Uchiyama	1994	Y	N	–	–	–	Y	–	N	–	–	–	–	–	–	–	–	–	–	–	–
Uchiyama	1996a	Y	Y	Y	Y	N	–	–	N	–	–	–	–	–	–	–	–	–	–	–	–
Uchiyama	1996b	Y	Y	Y	Y	N	–	–	N	–	–	–	–	–	–	–	–	–	–	–	–
van de Vate	1994	Y	Y	Y	Y	N	–	–	N	–	–	–	–	–	–	–	–	–	–	–	–
Vasquez and Hanbury	2011	Y	Y	N	Y	Y	N	–	N	–	–	–	–	–	–	–	–	–	–	–	–
Widiyanto et al.	2002	Y	Y	Y	Y	N	–	–	N	–	–	–	–	–	–	–	–	–	–	–	–
Wong and Tan	2014	Y	Y	Y	Y	Y	N	–	N	–	–	–	–	–	–	–	–	–	–	–	–

Table A-8. Description of Screening Columns

	Column	Criterion Description
First Screen	**A**	Written in 1980 or later?
	B	Full text available?
	C	Not abstract, poster, slideshow, conference paper <5 double-spaced pages, trade journal article <3 published pages?
	D	Written in English or translated version available?
	E	Covers geothermal energy?
	F	Performs or reviews LCA(s) and provides quantitative results?
	G	Evaluates electricity as an end product?
	P1	Passes screen 1?
Second Screen	**H**	Uses currently accepted LCA method?
	I	Employs a relevant impact assessment method?
	J	Examines at least two life cycle stages?
	K	Provides reasonable description of methods?
	L	Cites data sources?
	M	Reports a unique result?
	N	If appropriate, reports name of software or database used for analysis?
	O	Describes system characteristics quantitatively?
	P	Reports environmental impact estimates quantitatively?
	Q	Employs enough detail to scale results to per kWh?
	R	Examines modern or near-future system?
	P2	Passes screen 2?

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