Potential Economic Values of Minerals in Brines of Identified Hydrothermal Systems in the US

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ABSTRACT

Geothermal resources have been used as a source of clean and sustainable baseload power for many years. However, the upfront deployment costs of geothermal technologies are high. Various approaches are considered to make geothermal energy more economically attractive for developers. One potential approach to increase revenue is through recovery of minerals present in geothermal brines.

In this paper, we assess the mineral contents in brines from several US geothermal resource areas. Geothermal brine chemistry data were assembled from literature reviews and the brine mass-flow rates were estimated using GETEM with site-specific resource potential input from the GeoVision geothermal resource database. Our study shows that several minerals could be economically recovered from geothermal brines. Specially, potential revenues from recovery of Au, Cs, Rb, Li, and SiO_2 look promising for several sites. However, several outstanding technological, financial, market, as well as site-specific challenges need to be evaluated for economic recovery of these minerals.

1. Introduction

Several states in the western US have high potential to use geothermal energy. The United States Geological Survey (USGS) has defined multiple geothermal areas in the western US as identified hydrothermal resource areas (Williams et al., 2008). Geothermal power plants have been established at various hydrothermal resource areas over the last several decades, and there are numerous additional sites with power production potential. The potential growth of geothermal energy utilization in various market and technology advancement scenarios are the topic of an ongoing US Department of Energy (DOE) Geothermal Technologies Office (GTO) initiated

GeoVision Study. Specifically, the GeoVision Study has a broad goal to conduct a credible analysis of potential geothermal growth scenarios across multiple market sectors. Various factors such as technological advancements in exploration, drilling, system operations, hybridization, and additional revenue streams are being considered to make geothermal technologies as competitive and viable as other sources of renewable energy.

Geothermal power plants utilize subsurface natural heat for power production. The heat brought up to the surface via a large volume of hot brine (or steam) is captured for power production, and the post-power production brine is pumped back into the geologic formation to sustain the reservoir productivity. Chemical compounds contained in geothermal fluids are the product of long-duration subsurface water-rock interactions at high temperature. Specifically, chemically corrosive and complexing species such as hydrogen, chloride, sulfate, etc., ions in the geothermal fluids help leach metals from the rocks and sustain their mobility in the geothermal brines. Since geothermal plants utilize large volumes of brine, the overall extractable mass of certain minerals could be a source of significant additional revenue. However, geothermal power plants are conventionally built to recoup heat but not minerals. Therefore, development of cost-effective mineral recovery technologies could add an additional revenue stream and improve the economics of geothermal resource utilization.

As a part of the GeoVision Study, we are making an effort to assess the content of economic minerals and their potential values in brines of several identified hydrothermal resources. In our previous work (Neupane and Wendt, 2017), we assessed the mineral contents in numerous US geothermal features and presented economic values of various minerals at several operational geothermal power plants. In this paper, we extend our previous work to additional hydrothermal resource areas in the US. The majority of these areas do not have operational geothermal power plants, but they could be developed for power production and additional resources such as extractable minerals. In this study, we identify some target metals/minerals in geothermal brines and present potential economic revenues from recovery of these minerals. Our results are preliminary estimates, and we recommend further case-by-case detailed evaluations of the brine chemistry; sustainability; availability, efficiency, and processing costs for applicable extraction technologies; as well as analysis of potential market forces that could affect mineral commodity pricing.

2. Approach

Over the years, the chemical compositions of US geothermal brines have been measured and reported by various institutions and groups (e.g., USGS, DOE, states' water resources management agencies). Neupane and Wendt (2017) compiled a chemical database for over 2250 geothermal brines in the US. From that database, we selected a subset of data for several identified hydrothermal resource areas. The composition of brines representing these hydrothermal resource areas were assembled from various publicly available sources (e.g., White et al., 1963; Berkstresser, 1968; Mundorff, 1970; Young and Mitchell, 1973; Sanders and Mills, 1974; Reed, 1975; Mariner et al., 1974,1975,1980; Barrett and Pearl, 1976; Benoit, 1976; Mitchell, 1976a,b; Swanberg et al., 1977; Cosner and Apps, 1978; Leonard et al., 1978; Nehring and Mariner, 1979; Nehring et al., 1979; Mitchell et al., 1980; Dolenc et al., 1981; Goff et al., 1981; Trexler et al., 1982; Culp et al., 2015; Neupane et al., 2016a,b; Mattson et al., 2016; Neupane et al., 2017).

Brine mineral content and mass-flow rates are required to calculate the potential mass of minerals that could be recovered. The mass-flow rates of the potential geothermal plants at several hydrothermal resource sites are estimated using Geothermal Electricity Technology Evaluation Model (GETEM). GETEM is an Excel-based tool that estimates the cost associated with exploration, well field development, power plant construction along with operational costs and levelized cost of electricity (LCOE) from geothermal resource input specifications (Mines, 2008). In this analysis the resource input parameters for each site were obtained from the geothermal resource database used in the GeoVision Study market penetration analysis. When both the mass-flow rate and concentration of minerals are known, the total mass of minerals that could be recovered from the brines can be estimated.

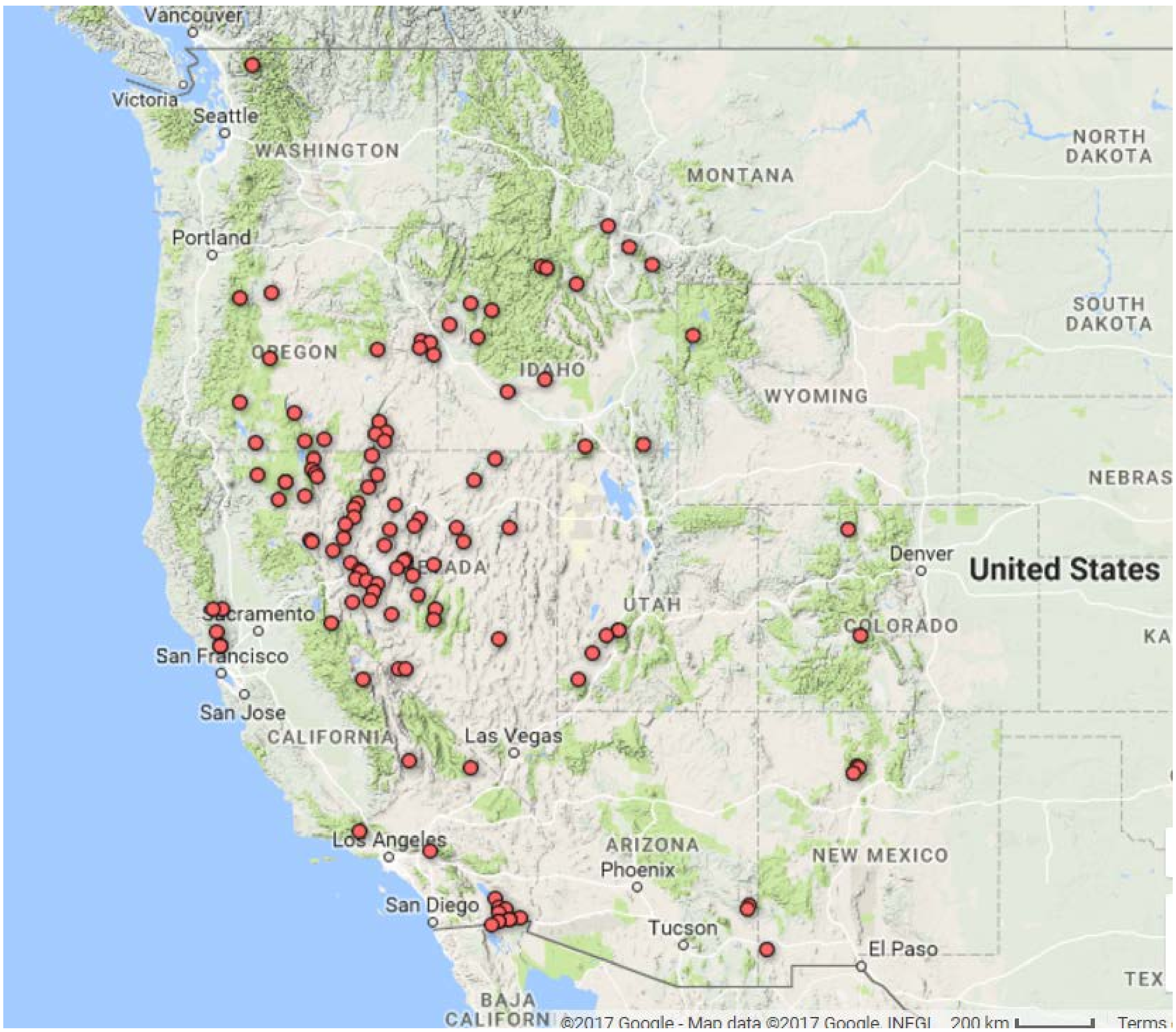

Figure 1: Map showing locations of identified hydrothermal resource areas in the western United States.

Table 1. Potential power capacity and GETEM estimated flow rates for several hydrothermal areas.

Sites	Capacity (MW)	Flow rate (kg/s)	Sites	Capacity (MW)	Flow rate (kg/s)
Alvord HS	24.4	1011	Lake City HS	125.9	3543
Amedee	7.0	525	Lakeview area	25.2	1096
Arrowhead HS	8.8	621	Latty HS	7.9	626
Baker HS	28.4	1901	Leach HS	9.4	565
Baltazor HS	25.7	1015	Lee HS	33.0	1068
Beowawe HS	51.6	706	Leonards/Seyferth HS	12.4	651
Big Creek HS	26.3	1109	Lightning Dock	5.7	293
Black Rock Point area	10.7	641	Little Valley area	18.3	976
Boyes HS	10.5	850	Long Valley - deep	59.4	920
Brady HS	22.6	485	Magic Reservoir area	11.3	939
Breitenbush HS	9.9	330	McLeod	12.3	741
Butte Springs (Trego)	9.1	632	Mickey HS	51.3	1297
Calistoga HS	21.1	810	Mitchell Butte	12.6	784
Canby (I'SOT)	11.8	709	Neal HS	37.0	1235
Clear Lake	36.5	241	Olene HS	10.3	840
Clifton HS	18.1	1466	Pinto HS	32.5	1139
Colado area	13.5	1129	Raft River	33.7	1159
Coso area	347.1	2501	Roosevelt HS	64.4	615
Cove Fort - Liquid	12.2	418	Routt	10.4	842
Crane/Cove Creek area	68.5	2040	Rowland HS	7.3	595
Crump's HS	55.0	1776	Salton Sea area	2103.1	12603
Darrough HS	14.2	913	San Emidio Desert area	77.2	1475
Deer Creek HS	19.6	980	Sespe HS	13.4	807
Desert Peak	19.3	262	Sharkey HS	12.5	851
Dixie HS	12.1	525	Silver Star HS	11.4	791
Dixie Valley Geothermal Field	116.6	1415	Smith Creek Valley	15.6	810
Dixie Valley Power Partners	97.4	729	Soda Lake area	46.5	705
Double HS area	11.7	705	Sonoma Mission Inn	7.9	625
Dyke HS area	6.8	553	Squaw HS	17.4	817
East Mesa (Deep)	66.3	1243	Stillwater area	60.8	1766
East Mesa (Shallow)	45.6	1231	Summer Lake HS	10.3	870
Emigrant	50.1	1255	Surprise Valley HS	9.7	676
Ennis HS	16.2	1121	Tecopa HS	11.3	643
Fernley area	27.8	829	The Needles	21.7	1346
Fort Bidwell	11.4	947	Thermo HS	6.9	386
Gillard HS	14.7	1197	Trout Creek	11.4	827
Gerlach HS	61.6	1504	Vale HS	56.5	2037
Gregson HS	8.9	722	Sulphur Spring/Valles	34.4	426
Hot Borax Lake	53.6	1732	Vulcan HS	12.6	876
Tuscarora HS	44.9	1419	Wabuska HS	9.5	634
Huckleberry HS	48.4	2884	Waunita HS	15.3	920
Humboldt House	113.0	1703	Battle Creek HS	17.5	804
Jemez Springs	10.8	876	Wendel	14.2	751
Kahneetah HS	7.6	545	West Valley Reservoir	15.7	725
Kellog HS	6.7	547	White Licks HS	11.3	937
Kelly HS	11.8	699	Wilbur Springs	36.7	1060

For this study, we have selected 92 identified hydrothermal resource sites in the US (Table 1). The main selection criteria for these sites was the availability of both brine chemical composition data and an estimate of brine mass-flow rate (estimated using GETEM with geothermal resource temperature and power generation potential input from the GeoVision Study geothermal resource database). Sites in Hawaii and Alaska are excluded in this study. The geographic distribution of these sites is shown in Figure 1. Table 1 lists GETEM-predicted mass-flow rates along with power generation capacity included in the GeoVision Study geothermal resource database. Using the mass flow rate and concentration of various minerals in brine for each hydrothermal site, we calculated the potential mass of minerals that could be available for recovery. Economic values of various minerals are calculated using market prices for various minerals listed in our previous paper (Neupane and Wendt, 2017).

3. Concentrations and economic values of recoverable mass of minerals

Since the measured values of all potentially economic minerals are not available for all brines, we have presented their concentrations and potential economic values of recoverable mass in separate tables (Tables 2 through 4). Specifically, Table 2 includes concentrations and economic values of precious metals (Au and Ag), Cs, Cu, Mn, Pb, Rb, Sr, and Zn. Similarly, Table 3 includes concentrations and economic values of Li, K, and B in geothermal brines. Table 4 shows concentrations and economic values of silica for some hydrothermal systems that have positive attributes for silica recovery.

Several assumptions were made to calculate the annual recoverable mass and potential revenue. As noted in our previous study, the most important assumptions are: the contents of minerals in the brine will not change significantly over time, all of production volume will be available for extraction of minerals, plant outages will be limited (operating 90% of the time), the extraction technology operates at a certain efficiency (80% extraction of each mineral from the brines), and there will be minimum market pricing volatility for the minerals of interest.

Table 2: Concentrations and potential economic values of various minerals in geothermal brines.

Sites	Ag	Au	Cs	Cu	Mn	Pb	Rb	Sr	Zn
Concentration (mg/kg)									
Alvord HS	0.02	0.1	0.2	0.05	0.02	0.06	0.33	0.92	
Beowawe HS	0.02		1.04	0.01	0.014	0.06	0.266	0.015	2.3
Breitenbush HS	0.02	0.1	0.1	0.01	0.22	0.06	0.18	0.73	
Crump's HS	0.02	0.1	0.1	0.01	0.03	0.06	0.07	0.12	
Dixie Valley Geothermal Field	<0.001	0.002	0.6	0.002	<0.002	0.002	0.62	0.45	0.02
East Mesa (Deep)	0.06	0.01		0.1	0.95	0.5		320	0.07
East Mesa (Shallow)	0.01	0.01	1.8	0.89	0.05	0.5	0.6	6.4	0.01
Gillard HS	0.07		0.1	0.12	0.02		0.02	0.09	0.13
Gerlach HS	0.02			0.01	0.02				
Hot Borax Lake	0.02	0.1	0.1	0.03	0.03	0.06	0.23	0.42	
Huckleberry HS	0.5			0.01	0.06	0.1			0.02
Kahneetah HS	0.02	0.1	0.1	0.01	0.02	0.06	0.02	0.05	
Lakeview area	0.02	0.1	0.1	0.01	0.02	0.06	0.04	0.32	

Sites	Ag	Au	Cs	Cu	Mn	Pb	Rb	Sr	Zn
Little Valley area	0.02	0.1	0.1	0.01	0.02	0.06	0.02	0.05	
Long Valley - deep	0.04	0.1	0.6	0.03	0.02	0.1	0.48	0.14	0.19
Mickey HS	0.02	0.1	0.1	0.05	0.02	0.06	0.2	0.15	
Mitchell Butte	0.02	0.1	0.1	0.01	0.02	0.06	0.02	0.05	
Neal HS	0.02	0.1	0.1	0.02	0.06	0.06	0.09	0.16	
Olene HS	0.02	0.1	0.1	0.01	0.02	0.06	0.02	0.58	
Salton Sea area	0.5	0.1	20	3	1260	90	25	600	500
Soda Lake area			1.1				0.47	3.77	
Summer Lake	0.02	0.1	0.1	0.02	0.02	0.06	0.02	0.07	
Trout Creek	0.02	0.1	0.1	0.03	0.02	0.06	0.1	0.3	
Vale HS	0.02	0.1	0.1	0.01	0.04	0.06	0.09		
Potential annual economic revenue ($/yr)									
Alvord HS	3.0×10^{5}	9.9×10^{7}	9.3×10^{7}	8.1×10^{3}	5	3.2×10^{3}	1.1×10^{8}	1.1×10^{3}	
Beowawe HS	2.1×10^{5}		3.4×10^{8}	1.1×10^{3}	2	2.3×10^{3}	6.3×10^{7}	12	8.7×10^{4}
Breitenbush HS	9.7×10^{4}	3.2×10^{7}	1.5×10^{7}	530	20	1.1×10^{3}	2.0×10^{7}	270	
Crump's HS	5.2×10^{5}	1.7×10^{8}	8.1×10^{7}	2.9×10^{3}	10	5.7×10^{3}	4.2×10^{7}	240	
Dixie Valley Geothermal Field	2.1×10^{4}	2.8×10^{6}	3.9×10^{8}	460	1	150	2.9×10^{8}	720	1.5×10^{3}
East Mesa (Deep)	1.1×10^{6}	1.2×10^{7}		2.0×10^{4}	280	3.3×10^{4}		4.5×10^{5}	4.7×10^{3}
East Mesa (Shallow)	1.8×10^{5}	1.2×10^{7}	1.0×10^{9}	1.8×10^{5}	20	3.3×10^{4}	2.5×10^{8}	8.9×10^{3}	660
Gillard HS	1.2×10^{6}		5.5×10^{7}	2.3×10^{4}	6		8.0×10^{6}	120	8.4×10^{3}
Gerlach HS	4.4×10^{5}			2.4×10^{3}	6				
Hot Borax Lake	5.1×10^{5}	1.7×10^{8}	7.9×10^{7}	8.4×10^{3}	10	5.6×10^{3}	1.3×10^{8}	830	
Huckleberry HS	2.1×10^{7}			4.6×10^{3}	40	1.5×10^{4}			3.1×10^{3}
Kahneetah HS	1.6×10^{5}	5.3×10^{7}	2.5×10^{7}	880	3	1.8×10^{3}	3.6×10^{6}	30	
Lakeview area	3.2×10^{5}	1.1×10^{8}	5.0×10^{7}	1.8×10^{3}	5	3.5×10^{3}	1.5×10^{7}	400	
Little Valley area	2.9×10^{5}	9.5×10^{7}	4.5×10^{7}	1.6×10^{3}	5	3.1×10^{3}	6.5×10^{6}	60	
Long Valley - deep	5.4×10^{5}	9.0×10^{7}	2.5×10^{8}	4.4×10^{3}	4	4.9×10^{3}	1.5×10^{8}	150	9.4×10^{3}
Mickey HS	3.8×10^{5}	1.3×10^{8}	5.9×10^{7}	1.0×10^{4}	6	4.2×103	8.7×10^{7}	220	
Mitchell Butte	2.3×10^{5}	7.6×10^{7}	3.6×10^{7}	1.3×10^{3}	4	2.5×10^{3}	5.2×10^{6}	40	
Neal HS	3.6×10^{5}	1.2×10^{8}	5.7×10^{7}	4.0×10^{3}	20	4.0×10^{3}	3.7×10^{7}	220	
Olene HS	2.5×10^{5}	8.2×10^{7}	3.9×10^{7}	1.4×10^{3}	4	2.7×10^{3}	5.6×10^{6}	550	
Salton Sea area	9.3×10^{7}	1.2×10^{9}	1.2×10^{11}	6.1×10^{6}	3.8×10^{6}	6.1×10^{7}	1.1×10^{11}	8.6×10^{6}	3.4×10^{8}
Soda Lake area	100	3.7×10^{4}	3.6×10^{8}	70		2	1.1×10^{8}	3.0×10^{3}	20
Summer Lake	2.6×10^{5}	8.5×10^{7}	4.0×10^{7}	2.8×10^{3}	4	2.8×10^{3}	5.8×10^{6}	70	
Trout Creek	2.4×10^{5}	8.1×10^{7}	3.8×10^{7}	4.0×10^{3}	4	2.7×10^{3}	2.8×10^{7}	280	
Vale HS	6.0×10^{5}	2.0×10^{8}	9.3×10^{7}	3.3×10^{3}	20	6.5×10^{3}	6.1×10^{7}		

Potential economic revenues from recovery of Au, Cs, and Rb appear to be promising for numerous sites (Table 2). For example, from the brine that could be used to generate 53.6 MW at the Hot Borax Lake hydrothermal system power could also yield over 350 million dollars of Au, Cs, and Rb each year. Economic values of Li for several hydrothermal systems are promising (Table 3). For some sites, the revenue from recoverable K could be attractive. For example, brines of the Salton Sea area, East Mesa, Battle Creek Hot Springs, and Wilber Hot Springs could provide millions of dollars' worth of K annually. However, the economic value of B does not appear promising for the majority of the hydrothermal system examined in this study.

Table 3: Concentrations and economic values of recoverable Li, K and B in geothermal brines.

Sites	Concentrations (mg/kg)			Economic value ($/yr)		
	Li	K	B	Li	K	B
Alvord HS	2.1	69	30	$1.7×10^6$	$1.4×10^6$	$4.3×10^5$
Amedee	0.1	5.4	4.7	$4.2×10^4$	$5.7×10^4$	$3.5×10^4$
Arrowhead HS	0.4	12	3.2	$2.0×10^5$	$1.5×10^5$	$2.8×10^4$
Baker HS	0.4	10		$6.0×10^5$	$3.8×10^5$	
Baltazor HS	0.22	8.2	2.1	$1.8×10^5$	$1.7×10^5$	$3.0×10^4$
Beowawe HS	2.6	14		$1.5×10^6$	$2.0×10^5$	
Big Creek HS		14			$3.1×10^5$	
Black Rock Point area		12	2.8		$1.5×10^5$	$2.6×10^4$
Boyes HS	1.65	20.2	15.7	$1.1×10^6$	$3.4×10^5$	$1.9×10^5$
Brady HS	1.3	62	4.7	$5.0×10^5$	$6.0×10^5$	$3.3×10^4$
Breitenbush HS	1.8	31	4.1	$4.7×10^5$	$2.0×10^5$	$1.9×10^4$
Butte Springs (Trego)		9.3			$1.2×10^5$	
Calistoga HS	1.8	8.9	11	$1.2×10^6$	$1.4×10^5$	$1.3×10^5$
Canby (I'SOT)		6.2	2.9		$8.8×10^4$	$2.9×10^4$
Clear Lake (	3.1	23	680	$5.9×10^5$	$1.1×10^5$	$2.3×10^6$
Clifton HS	2.6	82	0.64	$3.0×10^6$	$2.4×10^6$	$1.3×10^4$
Colado area	2.5	120	8.7	$2.2×10^6$	$2.7×10^6$	$1.4×10^5$
Coso area		12			$6.0×10^5$	
Cove Fort - Liquid	5	254	10	$1.7×10^6$	$2.1×10^6$	$6.0×10^4$
Crane/Cove Creek area	0.62	18	10	$1.0×10^6$	$7.3×10^5$	$2.9×10^5$
Crump's HS	0.4	11	14	$5.6×10^5$	$3.9×10^5$	$3.6×10^5$
Darrough HS	0.4	2.6	0.1	$2.9×10^5$	$4.7×10^4$	$1.3×10^3$
Deer Creek HS	0.15	5.3	0.24	$1.2×10^5$	$1.0×10^5$	$3.4×10^3$
Desert Peak	1.4	250	16	$2.9×10^5$	$1.3×10^6$	$6.0×10^4$
Dixie HS	0.38	6.5	0.89	$1.6×10^5$	$6.8×10^4$	$6.7×10^3$
Dixie Valley Geothermal Field	2.34	76.4	11.7	$2.6×10^6$	$2.2×10^6$	$2.4×10^5$
Dixie Valley Power Partners	2.29	69.5	11.6	$1.3×10^6$	$1.0×10^6$	$1.2×10^5$
Double HS area	0.06	4.5	1.8	$3.3×10^4$	$6.3×10^4$	$1.8×10^4$
Dyke HS area	0.09	4.3	1	$3.9×10^4$	$4.7×10^4$	$7.9×10^3$
East Mesa (Deep)	40	1050	9.8	$3.9×10^7$	$2.6×10^7$	$1.7×10^5$
East Mesa (Shallow)	4	150	7.5	$3.9×10^6$	$3.7×10^6$	$1.3×10^5$
Emigrant		2.5			$6.3×10^4$	
Ennis HS	0.26	17	0.61	$2.3×10^5$	$3.8×10^5$	$9.8×10^3$
Fernley area	1.6	38	5.6	$1.0×10^6$	$6.3×10^5$	$6.6×10^4$
Fort Bidwell	0.03	9.5	0.61	$2.2×10^4$	$1.8×10^5$	$8.3×10^3$
Gillard HS	1.01	13.2	0.4	$9.6×10^5$	$3.2×10^5$	$6.8×10^3$
Gerlach HS	1.9	124	0.1	$2.3×10^6$	$3.7×10^6$	$2.2×10^3$
Gregson HS	0.64	3.9	0.3	$3.7×10^5$	$5.6×10^4$	$3.1×10^3$
Hot Borax Lake	0.65	31	17	$8.9×10^5$	$1.1×10^6$	$4.2×10^5$
Tuscarora HS	0.7	41	0.77	$7.9×10^5$	$1.2×10^6$	$1.6×10^4$
Huckleberry HS		8.6	0.74		$5.0×10^5$	$3.1×10^4$
Humboldt House - Rye Patch	5.76	256	8.12	$7.8×10^6$	$8.7×10^6$	$2.0×10^5$
Jemez Springs	10.1	74.2	7.86	$7.0×10^6$	$1.3×10^6$	$9.8×10^4$
Kahneetah HS	0.52	3.4	2.6	$2.2×10^5$	$3.7×10^4$	$2.0×10^4$
Kellog HS	0.12	5.9	3.2	$5.2×10^4$	$6.4×10^4$	$2.5×10^4$
Kelly HS	0.15	6.5	3.8	$8.3×10^4$	$9.1×10^4$	$3.8×10^4$

Sites	Concentrations (mg/kg)			Economic value ($/yr)		
	Li	K	B	Li	K	B
Lake City HS		18	6.8		1.3×10^6	3.4×10^5
Lakeview area	0.15	8.5	6.9	1.3×10^5	1.9×10^5	1.1×10^5
Latty HS		1.7			2.1×10^4	
Leach HS	5.3	80		2.4×10^6	9.0×10^5	
Lee HS	0.7	26	2.4	5.9×10^5	5.5×10^5	3.7×10^4
Leonards/Seyferth HS	0.13	8.5	7.6	6.7×10^4	1.1×10^5	7.1×10^4
Lightning Dock		21			1.2×10^5	
Little Valley area	0.11	3.2	4.7	8.5×10^4	6.2×10^4	6.6×10^4
Long Valley - deep	2.8	45	15	2.0×10^6	8.3×10^5	2.0×10^5
Magic Reservoir area	1.18	23	0.08	8.8×10^5	4.3×10^5	1.1×10^3
McLeod	1.7	38	3.5	1.0×10^6	5.6×10^5	3.7×10^4
Mickey HS	1.1	35	11	1.1×10^6	9.1×10^5	2.0×10^5
Mitchell Butte	0.03	1.6	0.49	1.9×10^4	2.5×10^4	5.5×10^3
Neal HS	0.3	16	4.1	2.9×10^5	3.9×10^5	7.2×10^4
Olene HS	0.15	7.2	1	1.0×10^5	1.2×10^5	1.2×10^4
Pinto HS	0.45	23	7.5	4.1×10^5	5.2×10^5	1.2×10^5
Raft River	1.31	100		1.2×10^6	2.3×10^6	
Roosevelt HS	0.27	488	38	1.3×10^5	6.0×10^6	3.3×10^5
Routt	0.29	9	0.28	1.9×10^5	1.5×10^5	3.4×10^3
Rowland HS		4	0.41		4.8×10^4	3.5×10^3
Salton Sea area	440	14300	332	4.4×10^9	3.6×10^9	6.0×10^7
San Emidio Desert area	2.2	110	6.5	2.6×10^6	3.2×10^6	1.4×10^5
Sespe HS	0.76	16	13	4.9×10^5	2.6×10^5	1.5×10^5
Sharkey HS	0.47	16	1.6	3.2×10^5	2.7×10^5	1.9×10^4
Silver Star HS	0.38	6.7	0.26	2.4×10^5	1.1×10^5	2.9×10^3
Smith Creek Valley		8.1			1.3×10^5	
Soda Lake area	2.7	143	11.2	1.5×10^6	2.0×10^6	1.1×10^5
Sonoma Mission Inn	0.09	12	0.8	4.5×10^4	1.5×10^5	7.2×10^3
Squaw HS		533	9.7		8.7×10^6	1.1×10^5
Stillwater area	1.9	42	15	2.7×10^6	1.5×10^6	3.8×10^5
Summer Lake HS	0.15	4.6	6.9	1.0×10^5	8.0×10^4	8.6×10^4
Surprise Valley HS	0.1	5.5	5.7	5.3×10^4	7.4×10^4	5.5×10^4
Tecopa HS		16	5.1		2.1×10^5	4.7×10^4
The Needles	0.61	160	6.1	6.5×10^5	4.3×10^6	1.2×10^5
Thermo HS	1.3	52	0.93	4.0×10^5	4.0×10^5	5.1×10^3
Trout Creek	0.68	11	0.89	4.5×10^5	1.8×10^5	1.1×10^4
Vale HS	0.28	16	9.4	4.5×10^5	6.5×10^5	2.7×10^5
Sulphur Spring/Valles		24			2.0×10^5	
Vulcan HS		3			5.2×10^4	
Wabuska HS	0.53	15	1.8	2.7×10^5	1.9×10^5	1.6×10^4
Waunita HS	0.2	10	0.07	1.5×10^5	1.8×10^5	9.2×10^2
Battle Creek HS		552	7.6		8.9×10^6	8.7×10^4
Wendel	0.12	7.5	5.5	7.1×10^4	1.1×10^5	5.9×10^4
West Valley Reservoir	0.4	11	4.5	2.3×10^5	1.6×10^5	4.7×10^4
White Licks HS	0.24	17		1.8×10^5	3.2×10^5	
Wilbur Springs	33	493	0.21	2.8×10^7	1.0×10^7	3.2×10^3

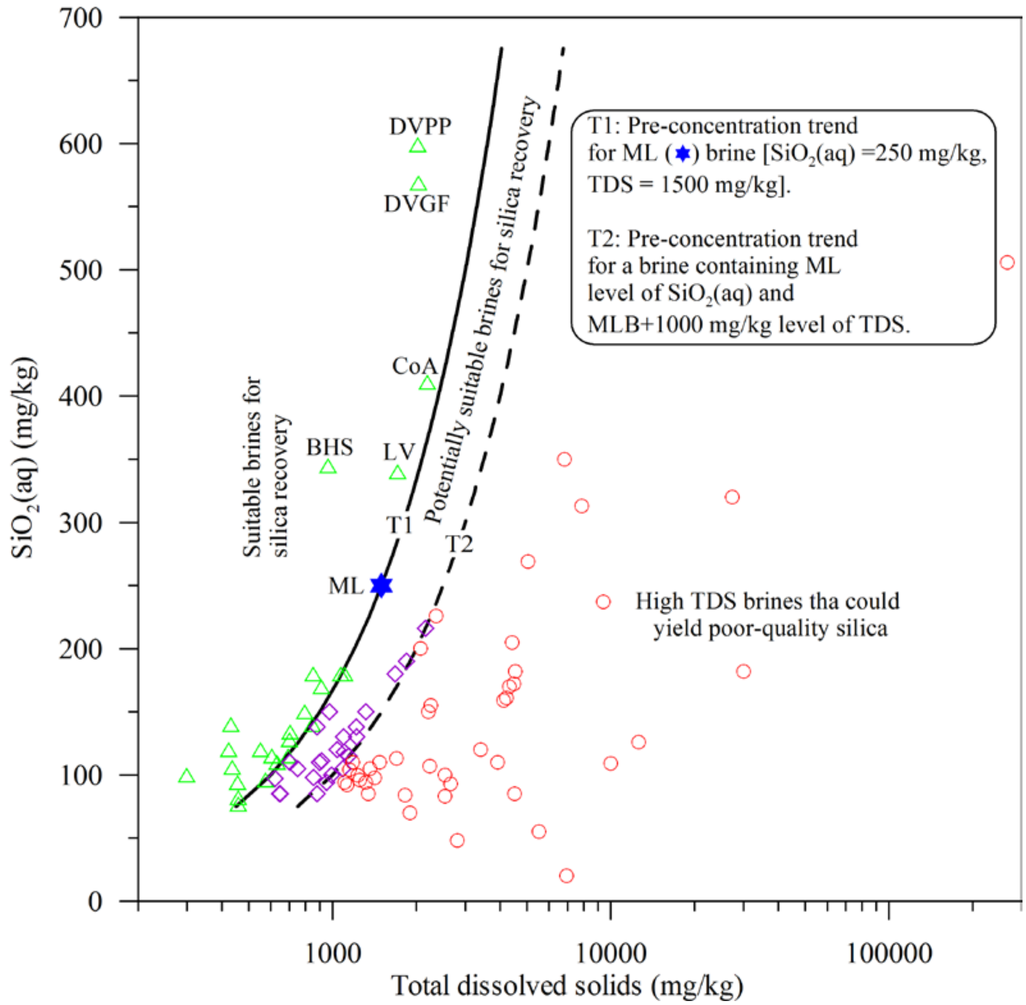

Figure 2: Concentrations of aqueous SiO_2 plotted against total dissolved solids (TDS) in geothermal brines. The brines with good, potentially suitable, and poor attributes for SiO_2 recovery are represented by green triangles (Δ), purple diamonds (◊), and red circles (○), respectively. (ML: Mammoth Lake, LV: Long Valley-deep, BHS: Beowawe Hot Springs, CoA: Coso area, DVGF: Dixie Valley Geothermal Field, DVPP: Dixie Valley Power Partners).

All geothermal brines are enriched in silica. For this study, we used our previous (Neupane and Wendt, 2017) approach to identify brines with positive attributes for silica recovery. This approach (Figure 2) uses the composition of the Mammoth Lake (ML) geothermal brine (TDS up to 1500 mg/kg, SiO_2 = 250 mg/kg) as a reference composition to develop a screening tool for identifying brines that could be used for SiO_2 recovery. The ML was selected as a reference brine because it was used in a pilot-plant for SiO_2 recovery by Bourcier et al. (2009). Since the natural concentration of SiO_2 in the ML brine is deemed low for direct extraction, Bourcier et al. (2009) employed a reverse osmosis technology to pre-concentrate aqueous SiO_2 by a factor of 2.5 to 3.5. Therefore, the dilution/concentration trends of ML are used as baselines to separate brines with good attributes for silica recovery. Any brine having ML+1000 mg/kg total dissolved solids could be considered as brine that could produce poor-quality silica. With this screening tool (Figure 2), we identified several identified hydrothermal systems that have brines potentially suitable for silica recovery. For these hydrothermal systems, the recovery of SiO_2 alone could potentially add millions of dollars of additional revenue (Table 4).

Table 4: Concentrations of SiO_2 and potential annual revenues ($/yr) from silica recovery.

Good brines			Potentially suitable brines		
Sites	SiO_2 (mg/kg)	Revenue ($/yr)	Sites	SiO_2 (mg/kg)	Revenue ($/yr)
Baker HS	140	1.1×10^{7}	Amedee	138	2.9×10^{6}
Baltazor HS	150	6.0×10^{6}	Arrowhead HS	94	2.3×10^{6}
Beowawe HS	345	9.7×10^{6}	Big Creek HS	150	6.6×10^{6}
Calistoga HS	134	4.3×10^{6}	Canby (I'SOT)	111	3.1×10^{6}
Coso area	411	4.1×10^{7}	Double HS area	105	2.9×10^{6}
Crane/Cove Creek area	180	1.5×10^{7}	Dyke HS area	85	1.9×10^{6}
Crump's HS	180	1.3×10^{7}	Gregson HS	85	2.4×10^{6}
Darrough HS	106	3.8×10^{6}	Hot Borax Lake	190	1.3×10^{7}
Deer Creek HS	120	4.7×10^{6}	Kellog HS	85	1.8×10^{6}
Dixie HS	115	2.4×10^{6}	Kelly HS	110	3.1×10^{6}
Dixie Valley Geothermal Field	569	3.2×10^{7}	Lake City HS	118	1.7×10^{7}
Dixie Valley Power Partners	599	1.7×10^{7}	Lee HS	180	7.6×10^{6}
Fort Bidwell	82	3.1×10^{6}	Lightning Dock	138	1.6×10^{6}
Huckleberry HS	170	1.9×10^{7}	Olene HS	98	3.3×10^{6}
Lakeview area	140	6.1×10^{6}	Pinto HS	150	6.8×10^{6}
Latty HS	100	2.5×10^{6}	Routt	97	3.2×10^{6}
Little Valley area	115	4.5×10^{6}	Silver Star HS	110	3.5×10^{6}
Long Valley - deep	340	1.2×10^{7}	Surprise Valley HS	100	2.7×10^{6}
Mitchell Butte	94	2.9×10^{6}	Trout Creek	105	3.5×10^{6}
Neal HS	180	8.8×10^{6}	Vale HS	130	1.1×10^{7}
Rowland HS	96	2.3×10^{6}	Sulphur Spring/Valles	216	3.7×10^{6}
Smith Creek Valley	128	4.1×10^{6}	Wabuska HS	115	2.9×10^{6}
Sonoma Mission Inn	77	1.9×10^{6}	Wendel	120	3.6×10^{6}
Vulcan HS	120	4.2×10^{6}	West Valley Reservoir	130	3.7×10^{6}
Waunita HS	110	4.0×10^{6}			

4. Cost of power and comparative values of recoverable minerals

4.1 Cost of power generation

The Business-As-Usual Scenario GETEM-estimated costs of power generation (as LCOE) for the sites considered in this study range from $0.045 to $0.368 per kWh (Figure 3). The DOE-GTO seeks to lower the LCOE of the near-term hydrothermal growth to $0.06/kWh by 2020 through developing, demonstrating, and deploying innovative technologies (DOE-GTO, 2017). The GETEM simulations indicate that only 5 sites out of the 92 sites can produce electricity at that desired level of LCOE in the Business-As-Usual scenario, and the remaining sites will have LCOE > $0.06 /kWh (Figure 4). It is expected that the potential additional revenue from the recovery of minerals (or development of some other cost saving technologies) could help decrease the LCOE for these sites and make them competitive resources in the future.

Figure 3. Cost of power generation and economic value of recoverable minerals in the brines.

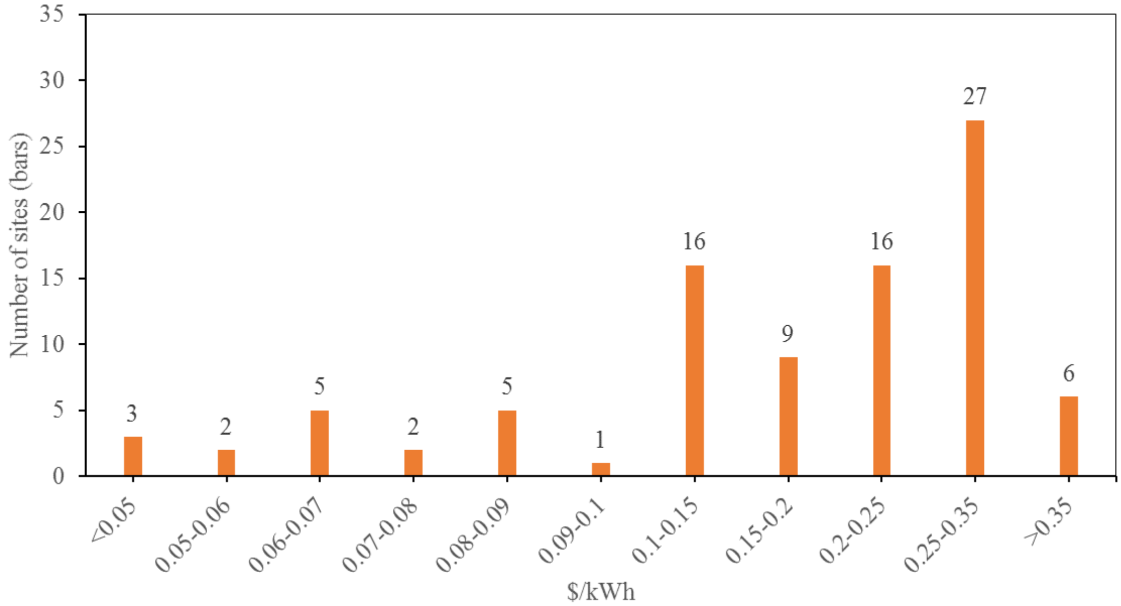

Figure 4. Cost of geothermal power generation without extraction of minerals from brines.

4.2 Unit value of recoverable minerals

To assess the economic effect of minerals' extraction on LCOE, we calculated the per unit value of recoverable minerals from brines for all hydrothermal sites. For this calculation, we again assumed that all plants will be operated for 90% of the year at the capacity given in Table 1. Then the total annual economic value (in $/yr) of minerals for each site was obtained by adding economic values of all recoverable minerals (Tables 2 through 4). Similarly, the total annual power (in kWh) was calculated assuming a 0.9 capacity factor for each site with the power capacity given in Table 1. Finally, the unit value (in $/kWh) of recoverable minerals for each site was calculated by dividing the total annual economic values of minerals by the total annual power. This calculation provides the unit value of minerals from the total mass of brine used to generate 1 kWh of electricity [hereafter, we express this directly as 1 unit (or 1 kWh) value of minerals] and also helps compare mineral value directly with the cost of power generation. Besides calculating the total value of minerals, a set of similar calculations were carried out without accounting for the economic values of recoverable SiO_2. It is assumed that the market for high-quality SiO_2 may not be adequate for a sustainable recovery of SiO_2 from all potential geothermal sites. Non-silica per unit value of minerals would help evaluate the impact of other minerals' to lower LCOE.

An important limitation in our approach for direct comparison between the cost of power generation and the value of minerals is that unlike the cost of power generation, our economic value of minerals does not include the upfront capital and operational costs for the recovery system. We used GETEM estimated LCOE as a cost of power generation to these sites. GETEM includes the capital, operation, maintenance, financial, etc., costs while estimating LCOE (Mines, 2008). However, our economic value of minerals does not account for any of the costs that would be incurred when establishing and operating mineral extraction facilities. For more meaningful comparison, unit economic value of minerals derived by accounting for capital, operation, maintenance, and other financial costs would be required. As we stated in our previous work (Neupane and Wendt, 2017), we do not have adequate information regarding the technology deployment as well as capital and other associated costs for mineral extraction facilities and activities.

Figure 3 shows the value of recoverable minerals for all sites both including and excluding the potential revenue from extraction of SiO_2. The potential unit value of minerals (with or without SiO_2) for these sites ranges from negligible to up to $13.9/kWh. Figure 5a illustrates the distributions of hydrothermal sites according to the per unit value of minerals. When all recoverable minerals are considered, 15% of the sites (14) have negligible (<$0.01/kWh) value of minerals. Furthermore, the number of sites (50) with mineral value <$0.01/kWh increased to more than half of the total sites examined in this study when the potential value from extraction of SiO_2 was excluded from the calculations (Figure 5b). For most of the sites with $0.01 to 0.05/kWh value of minerals, the potential mineral revenue is likely to be eliminated if the extraction of SiO_2 is excluded. However, the sites with the highest economic impacts from mineral recovery maintain the similar level of potential revenue from minerals since the main minerals to be extracted from these sites are non-SiO_2, such as Cs, Li, Rb, and precious minerals (Tables 2 through 4; Figure 5).

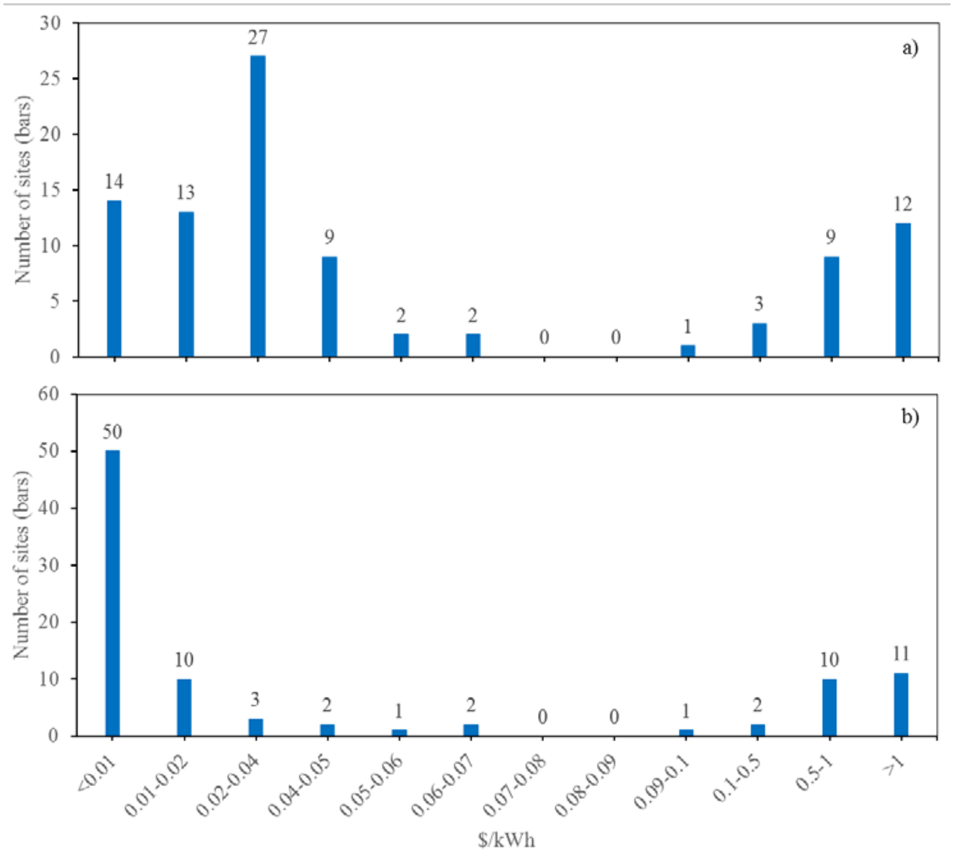

Figure 5. Economic values of recoverable minerals including silica (a) and excluding silica (b) in geothermal brines.

4.3 Impact of minerals on cost of power generation

Figure 6 shows the distribution of the cost of power generation if the revenue from potential mineral extractions is included. Inclusion of revenue from all recoverable minerals could increase the number of sites with LCOE ≤ 0.06 \$/kWh from 5 sites (Figure 4) to 29 (Figure 6a). Similarly, if potential revenue from SiO_2 is excluded, about 28 sites are likely to generate power with LCOE ≤ 0.06 \$/kWh (Figure 6b).

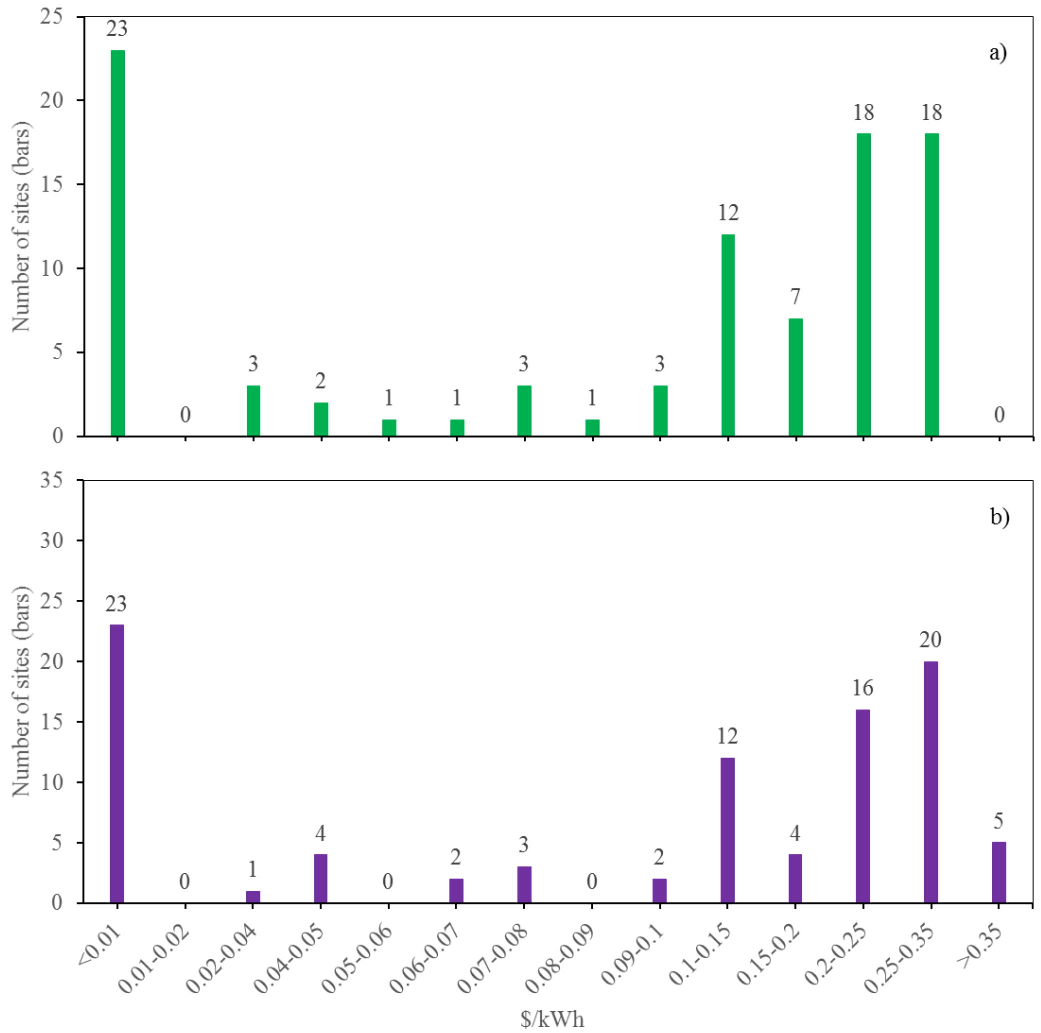

Figure 6. Cost of geothermal power generation with extraction of all recoverable minerals (a) and all but silica minerals (b) from brines.

4.4 Relative value of minerals in brines

The value of minerals in terms of the percentage of the power generation cost is also calculated and presented in Figure 7. The US hydrothermal resource areas mostly show a bimodal distribution in terms of their potential mineral values relative to the cost of power production. Many sites generate small revenue from potential mineral recovery. The number of sites that would yield <10% of revenue (relative to power) from all recoverable minerals is 20, and this number increases to 54 if the potential revenue from recoverable SiO_2 is excluded. A large number of sites (40) could yield 10-25% of relative revenue if all minerals are considered. Only a few sites (8 and 1 sites, respectively) have potential revenue from mineral recovery that could account about 25-50% and 50-100% relative revenue. However, there are some other sites that can add significant revenue from minerals, potentially exceeding the cost to generate power. For example, the value of minerals in brines from 23 sites are high enough to completely offset the cost of power generation. Therefore, it appears that the sites that show the greatest promise for mineral recovery are very good, and could provide better revenue from minerals than from power. Even though we did not include the capital and operational costs for the mineral extraction facilities and activities, these findings indicate that for these high-mineral-potential sites, the augmentation of mineral extraction plants along with power plants could be very economic, or at minimum, such efforts could help make geothermal power more cost competitive by decreasing LCOE. In the meantime, they could also be reliable domestic sources for some minerals. In contrast, for many sites, the relative revenue contribution from recoverable minerals is likely marginal and may not be adequate to decrease the LCOE to the GTO's desired level.

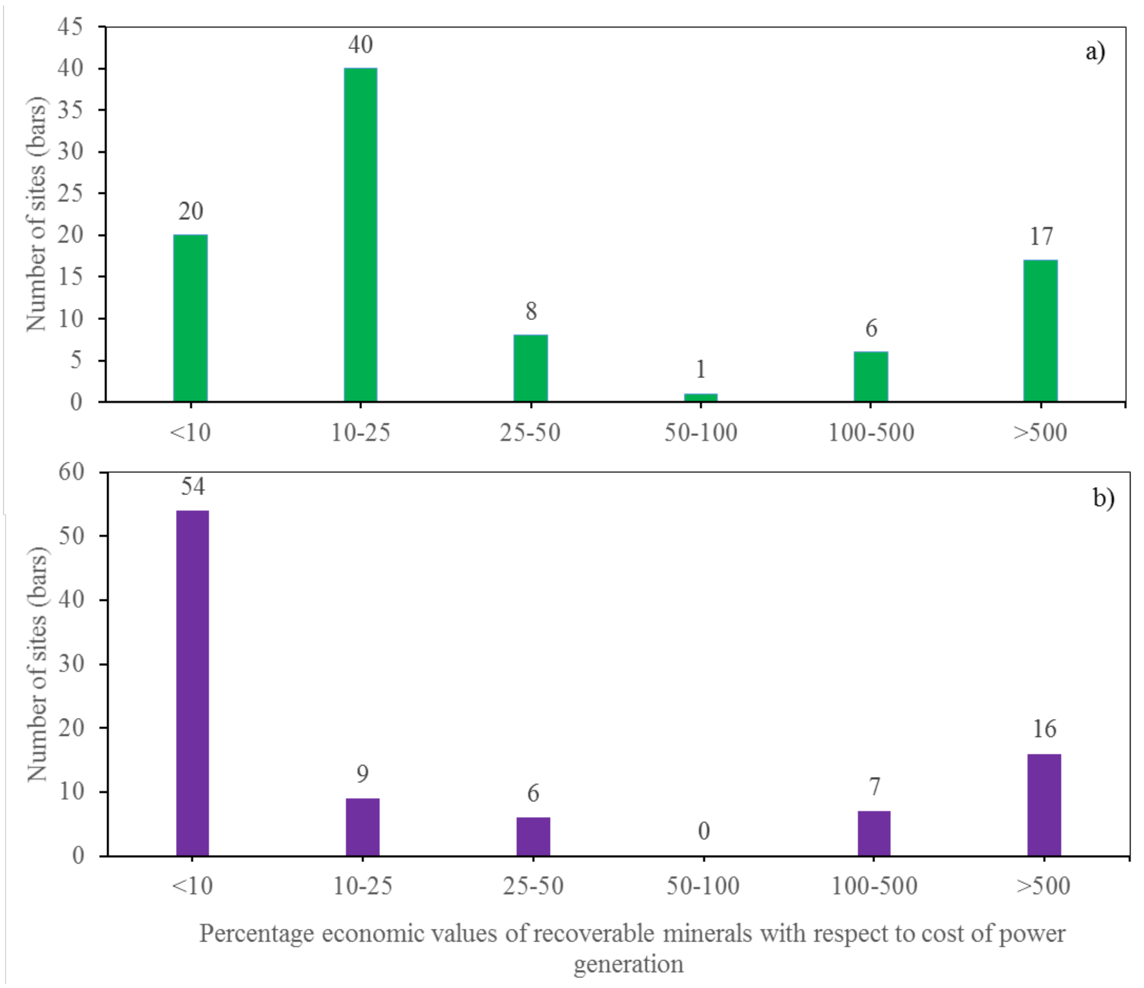

Figure 7. Relative economic values of recoverable all minerals (a) and all but silica minerals (b) with respect to the cost of power generation.

4. Conclusions

In this study, we assembled brine compositions for several identified hydrothermal resource areas. The mineral loadings in the geothermal brines from these areas vary, ranging from extremely low levels for some minerals to high levels for others. In general, our resource assessment shows that numerous geothermal brines in the US contain concentrations for some minerals that could, if successfully recovered, potentially provide a new value-added revenue stream to the geothermal industry.

Our assessment shows that for several hydrothermal resource areas, economic potential from recovery of precious metals (Ag and Au), Cs, Rb, Li, and SiO_2 are very promising. However, none of these minerals are currently recovered from the geothermal brines in the US. As we reported previously, recovery technologies for the majority of these minerals have been at low technology readiness level (TRL), and mostly limited to laboratory bench-scale level analyses. Only technologies for extraction of Li and SiO_2 have been tested with pilot-scale plants. Pilot-scale testing of other mineral recovery technologies needs to be performed prior to commercial-scale deployment. For sustainable recovery, the extraction technology needs to be designed for the mineral types, contents, overall chemistry of the target brines, and likely future market conditions for the mineral commodities.

Our comparative assessments indicate that for several sites the value of minerals in brines outweigh the cost of power generation. When all recoverable minerals are considered, brines of 23 sites (out of 92 sites) contain greater value of minerals than the cost to generate power from those brines. Although extraction of all recoverable minerals may not be feasible because of the minimum total value of individual minerals, lower technology readiness levels of extraction technologies, and adverse market forces, some site-specific minerals can be chosen from a list of recoverable minerals for extraction. If such targeted mineral(s) extraction facilities are added or established along with power generation infrastructure, it is very likely that the revenue from minerals could offset some of the cost associated with generation of power. Our study indicate the number sites that could generate power at GTO's desired 2020 LCOE value of $0.06 /kWh could increase from 5 to 29 if revenues from all recoverable minerals are considered. However, evaluation and identification of the most valuable minerals along with the evaluation of extraction technology readiness levels, capital/operating costs, and market forces needs to be performed before establishing mineral extraction facilities at each geothermal site.

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