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Geothermal Desalination GeoVision Case Study Analysis: Multiple Effect Distillation

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thermal desalination; geothermal energy; multiple effect distillation; membrane distillation; switchable polarity solvent forward osmosis

ABSTRACT

Multiple effect distillation (MED) was evaluated as the baseline technology for geothermal desalination. MED desalination plant mass & energy balances were modeled using a simplified method described in the open literature. GETEM was used to calculate hydrothermal and EGS resource costs in the Business-As-Usual and Exploration De-Risk GeoVision Study Scenarios. The levelized cost of water (LCOW) was evaluated for geothermal resources in the temperature range of 100°C to 200°C.

The LCOH from geothermal resources in the scenarios evaluated is cost competitive with many of the heat sources examined for MED desalination applications discussed in the literature. In the Business-As-Usual Scenario a hydrothermal resource achieves the LCOW cost target of $1.50/m³ with resource temperatures of approximately 150°C and greater. A hydrothermal resource in the Exploration De-Risk Scenario achieves the LCOW cost target of $1.00/m³ at a resource temperature of 200°C. In all cases evaluated, higher temperature geothermal resources demonstrate increased ability to achieve the specified LCOW cost targets.

The degree to which the geothermal resource, feed water source, cooling water, water market, and concentrate disposal site are co-located will have a significant impact on the viability of any geothermal desalination application. In practice, due to large variations in resource characteristics, site attributes, and application requirements, the economic and logistical feasibility of geothermal desalination is likely to be highly site- and application- dependent. Although EGS resources in the Exploration De-Risk Scenario do not achieve the LCOW cost target at the resource temperatures evaluated, EGS resources could be deployed at locations where hydrothermal resources do not exist, which would help to address co-location challenges.

1. Overview

The most widely used desalination technologies include thermal- and membrane-based technologies. Geothermal energy can be used to drive a desalination process, either through directly providing the heat to drive a thermal desalination process, or by providing electrical power for driving a reverse osmosis (RO) membrane-based desalination process. Numerous different geothermal desalination configurations have been studied, and several have been pilot tested (European Geothermal Energy Council, 2007, Sephton Water Technology, 2012, Karytsas et al., 2004, Gutierrez and Espindola, 2010, Bundschuh et al., 2015, Loutatidou and Arafat, 2015, Goosen et al., 2010, Mahmoudi et al., 2010, Gude et al., 2010, Akar and Turchi, 2016). As noted by Gude et al. (2010), there are numerous benefits of using geothermal energy for desalination including:

- Geothermal energy provides a stable and reliable heat supply ensuring the stability of thermal desalination
- Geothermal production technology (extraction of hot water from underground reservoirs) is mature
- Typical geothermal source temperatures are in a temperature range suitable for low-temperature MED desalination
- Geothermal desalination is cost effective, and simultaneous electricity production is possible
- Geothermal desalination is environmental-friendly, as only renewable energy is used with no emissions of air pollutants or greenhouse gases
- Geothermal desalination saves imported fossil fuels which can be used for other purposes.

In this analysis multiple-effect distillation (MED), also known as multiple-effect evaporation (MEE) or multiple effect boiling (MEB), is evaluated as the baseline technology for geothermal desalination. MED is a thermal desalination technology with numerous attributes that make it well suited for use in geothermal desalination applications. MED is a mature technology that has been the process of choice for industrial low-grade-heat-driven desalination since the early 1990s. MED has high reliability with low pretreatment requirements and low electrical power requirements compared to other thermal desalination technologies such as multi-stage flash (NRC, 2008). Low enthalpy geothermal heat sources (T>60°C) may be utilized for use with MED (European Geothermal Energy Council, 2007), and MED technology has been demonstrated by Sephton Water Technology to produce up to 20 m^3/day of freshwater from Salton Sea water using 100°C geothermal steam (Sephton Water Technology, 2012) and also utilized on the Greek Island of Kimolos to produce 80 m^3/day of freshwater using a 60-61°C geothermal resource (Ghaffour et al., 2015). Additionally, the reliability and robust fouling resistance of MED technology make it suitable for co-produced water treatment (Thiel et al., 2015), which is also a potential geothermal desalination application.

The MED process uses steam to evaporate a portion of the brine fed to the first effect. The distillate vapor is subsequently used to provide heat input to subsequent, lower temperature effects to maximize the energy utilization of the process. Figure 1 illustrates the configuration and operation of a representative MED system (Darwish and Abdulrahim, 2008).

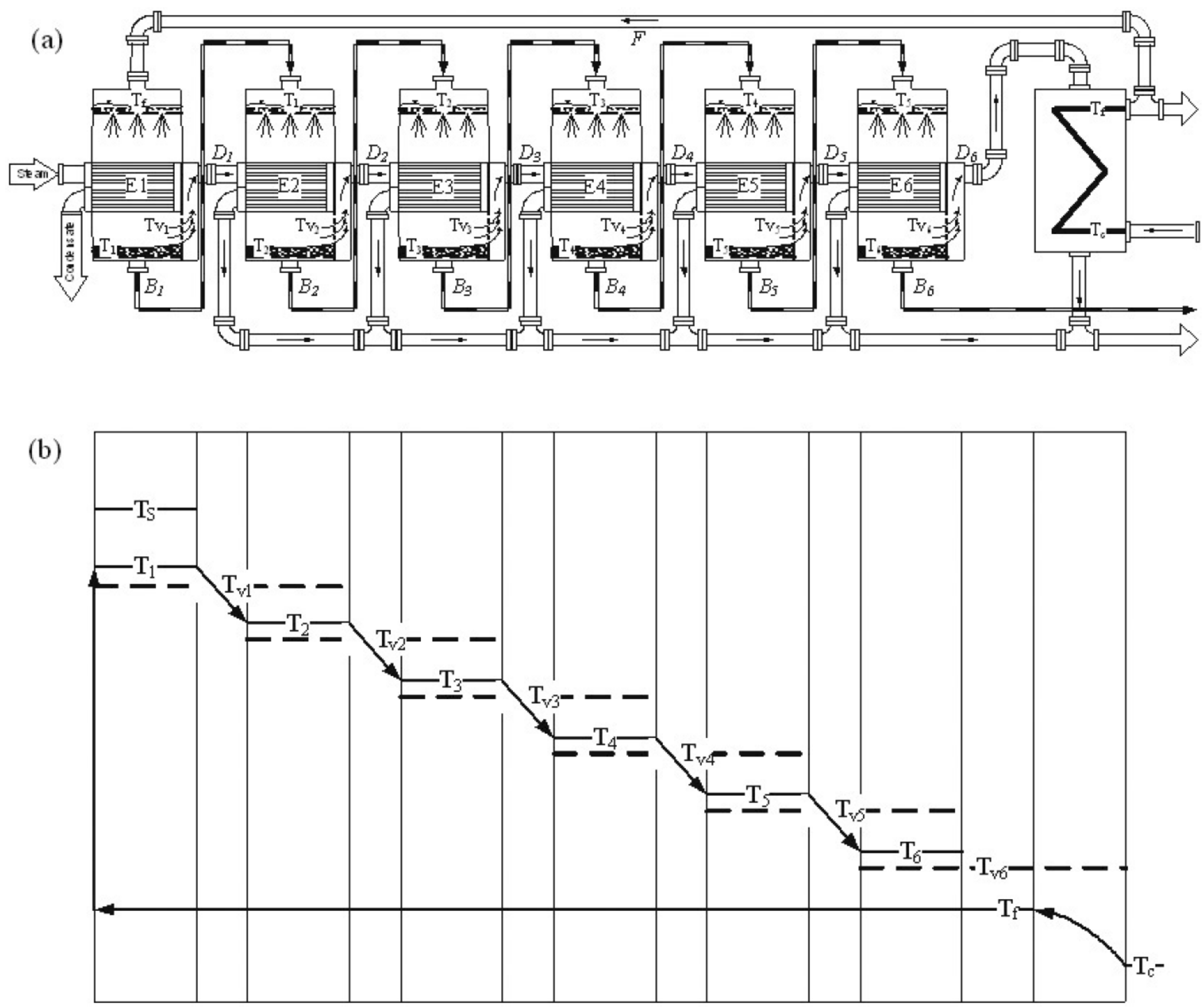

Figure 1. (a) Forward feed six-effect distillation system; (b) temperature distribution through the effects (Darwish and Abdulrahim, 2008).

2. Methodology

In order to evaluate the cost of geothermal desalination in each of the scenarios investigated, several case studies were analyzed. Each case study was defined by the selection of a resource type, a GeoVision Study scenario, and the range of resource temperatures evaluated. While in practice geothermal desalination site characteristics and project requirements will vary on a site-by-site basis, the case study analyses were performed using parameters selected to provide generalized results that would be instructive for determining the resource types, resource conditions, and scenarios that would be best suited for geothermal desalination applications.

In this analysis it is assumed that the geothermal resources evaluated are used exclusively for the purpose of providing heat to a geothermal desalination plant. Although the geothermal resource costs are assumed to include the drilling, field gathering system, pumps, and O&M costs, it is assumed that the geothermal resource is developed at an identified site such that there is no cost associated with geothermal exploration. However, the cost of drilling unsuccessful production and injection wells is included in the drilling costs. The geothermal resource costs are calculated using the GETEM model with input parameters from applicable GeoVision Study scenarios.

The GeoVision scenarios evaluated include the Business-As-Usual Scenario with a brownfield hydrothermal resource and the Exploration De-Risk Scenario with brownfield hydrothermal and EGS resources. Since this analysis assumes a brownfield site it is likely that the desalination process would be located at the same site as new or existing power plants, which would also provide the benefit of readily available electrical power.

Each case study analysis assumed a project size based on the use of three geothermal production wells, each with a flow rate defined by the applicable GeoVision Scenario evaluated (generally 110 kg/s). Geothermal production fluid temperatures of 100°C to 200°C were evaluated. The steam used for thermal energy input to the MED process is provided by flashing the geothermal production fluid (Darwish et al., 2006, Goosen et al., 2010, Loutatidou and Arafat, 2015, Sephton Water Technology, 2012). The flash pressure is selected such that the steam conditions will be consistent with those reported in various MED desalination modeling analyses available in the open literature (Darwish et al., 2006, El-Dessouky et al., 1998, Mistry et al., 2013, Al-Sahali and Ettouney, 2007). Geothermal resources with $T \geq 125°C$ are coupled with an 8 effect MED process that uses 0.31 bar steam (70°C), while geothermal resources with $T < 125°C$ are coupled with a 6 effect MED process that utilizes 0.16 bar steam (55°C).

The quantity of water that could be desalinated from each of the geothermal resources evaluated was determined by developing a simplified MED model based on the approach used by Darwish et al (Darwish et al., 2006). The MED model was used to evaluate gained output ratio (GOR), or the ratio of the distillate output to the steam input for the applicable MED process configuration and operating conditions. The number of effects in the MED model was selected to result in a ΔT between effects of approximately 4°C, which provides a good balance between process cost (lower ΔT results in higher heat exchanger area requirements) and efficiency (higher ΔT results in fewer effects; GOR generally cannot exceed the number of effects).

The feed water is assumed to come from a generic saline water source and to have a total dissolved solids (TDS) concentration of 30,000 ppm. The MED process performance is based on the assumption that the feed water is concentrated to 60,000 ppm. The source of this generic saline feed water could be seawater, water from a saline aquifer, brackish water, wastewater, or geothermal brine. Use of geothermal brine is considered unlikely as use of this fluid could result in reservoir drawdown at hydrothermal sites, and EGS resources require the net addition of water in order to transfer the geothermal heat to the surface.

In this analysis no cost is associated with acquisition of the saline water feed stream, but this assumption is not expected to hold for many potential geothermal desalination applications since at a minimum it would generally be expected that some sort of infrastructure would be required to provide the source water to the desalination process. Additionally, pretreatment is a site specific issue that can contribute to the costs and influence the feasibility of a desalination process. The degree to which the feed stream contains potential fouling agents such as scalants, particulates, and biological components may have a major impact on the overall costs (Miller, 2003). In this analysis a generic operating cost of $0.025/m^3 was included for cleaning, anti-scalant, and antimicrobial chemicals (Ettouney et al., 2002).

Additional site-specific considerations include the MED process cooling source and the concentrated brine disposal. The MED process model assumes use of 28°C cooling water that is provided at no cost. In practice, several process cooling options could be used. Process cooling could be provided by the feed water source, or through use of a cooling tower or air-cooled condenser. Of these options, the use of the feed water source for cooling would likely be the most economical, but includes the limitation that a volume of water in excess of that required for the process feed stream would be required. Similarly, no cost was assigned to disposal of the concentrated brine. In seawater desalination applications the concentrated brine can often be returned to the saline water intake source. Concentrated brine disposal is particularly a problem for inland desalination (Miller, 2003). The geothermal reservoir may be a suitable destination for concentrated brine disposal, but further study would be required to determine whether this would adversely impact injection well or reservoir performance.

Another important site-specific consideration is the extent to which the geothermal resource, the saline water source, and an application/market for the purified water product are co-located. If any of these resources is in a location removed from the others, significant costs may be incurred in order to transport all resources to a common site. Since transport costs increase with distance, there will be a maximum allowable radius over which these resources can be obtained; this analysis does not consider costs associated with transporting material or energy for geothermal desalination applications.

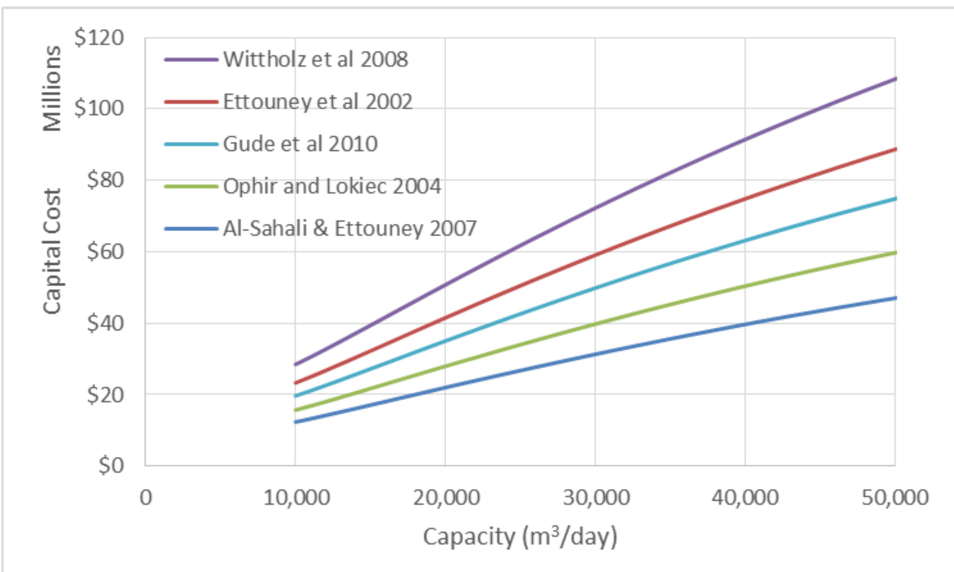

Figure 2. MED desalination plant capital costs vs plant capacity. Curves generated using power law scaling relation based on capital costs reported in referenced literature sources.

MED process capital costs were obtained by scaling values reported in the open literature. The literature includes numerous cost estimates of MED desalination applications, although these costs were reported over a period of several decades for disparate worldwide locations and desalination applications. Figure 2 is a plot of several of the reported capital costs scaled over various MED desalination plant capacities using a scaling exponent of 0.83 as derived from a desalination plant cost database compiled by Wittholz et al. (2008). The reference plant capital costs were based on those listed by Gude et al. (2010) for a 20,000 m^3/day MED desalination plant since this data produced the median capital cost curve from the data evaluated. MED process operating costs include electric power consumption, chemicals, labor, and replacement parts. Estimates for each of these operating cost components were obtained from various literature sources. A summary of all input parameters used to determine the costs of the geothermal resource (calculated using GETEM with applicable GeoVision Scenario inputs) and the MED desalination plant is provided in Table 1.

3. Target costs and applications

This analysis did not calculate mass & energy balances or estimate costs for non-geothermal energy based desalination applications. Instead, the literature was reviewed to determine applicable desalination product water costs. The unit cost of large-scale seawater desalination lies in the range of \$0.50 and \$2.00 per m^3 (Wittholz et al., 2008). Water purchase agreement costs for the Carlsbad RO Desalination Plant are reported as \$2131 to \$2367 per acre-ft (\$1.73 to \$1.92 per m^3) (San Diego County Water Authority, 2016), although this price is stated to be about twice the price of alternative water sources (Turchi et al., 2015). While there may be select sites where geothermal energy could be used to desalinate seawater, more opportunities are likely to exist in non-coastal areas of the US where geothermal resources are abundant and fresh water is scarce. Geothermal desalination in the interior US would likely be performed at a smaller scale than the seawater desalination plants, and would likely be used to treat water from saline aquifer, brackish water, or wastewater sources. The current wholesale cost for small-scale thermal desalination is on the order of \$2–\$3/m^3, which is at the high end of retail water rates in major U.S. cities (Turchi et al., 2015).

Depending on the heat source, a significant fraction of thermal desalination costs can be associated with the thermal energy. Al-Sahali and Ettouney estimate that steam costs account for \$0.30/m^3 of the product water cost for an MED desalination application in which steam is extracted from a steam Rankine cycle power plant (Al-Sahali and Ettouney, 2007). Following the calculations of Kesieme, it is estimated that steam costs account for approximately \$0.70/m^3 of the product water cost in an MED application in which the price of the steam is \$0.0078/kg (\$3.53/MMBtu) and MED process thermal energy requirements per unit of product water equal 60 kWh/m^3 (Kesieme et al., 2013). These represent relatively high energy costs for MED desalination, and suggest that there are opportunities for cost reductions through the use of geothermal heat. As noted by Turchi et al, membrane distillation thermal desalination product water cost could be less than \$1.00/m^3 if thermal energy is inexpensive, as in waste heat or low-cost geothermal energy applications. Such a cost would be competitive with the best desalination applications in the world (Turchi et al., 2015).

For this analysis, desalination applications with water product costs of \$1.50/m^3 or less are likely cost competitive in various domestic water markets, and deployment of geothermal desalination plants at this price is possible in the Business-As-Usual Scenario provided that low cost sources of feed water and process cooling, as well as suitable water market and/or end use application are readily available. Therefore, \$1.50/m^3 is specified as the Business-As-Usual (reference) scenario price target in this analysis.

Table 1. Thermal Desalination Analysis Input Parameters

Input Parameter	Value	Reference or comment
Geothermal Resource		
Resource depth or temperature gradient	1500 m	Hydrothermal resources
	5°C/100 m	EGS resources
Temperature range evaluated	100-200°C	25°C increments evaluated
Reinjection temperature	70°C for production T≥125°C 55°C for production T<125°C	Production fluid flashed to generate steam at pressure corresponding to the reinjection temperature
Production fluid flow rate	330 kg/s	Value corresponds to three production wells at GeoVision Scenario default flow rate (110 kg/s for both Business-As-Usual and Exploration De-Risk Scenarios)
Exploration drilling cost	None	No costs included for exploration drilling; however, geothermal drilling does include costs for failed wells as calculated by GETEM
MED Capital Costs		
Reference plant capacity	20,000 m^3/day	Gude et al. (2010)
Reference plant capital cost	$35MM	Gude et al. (2010), Additional data for CAPEX estimation provided in Al-Sahali and Ettouney (2007), Ettouney et al. (2002), Ghaffour et al. (2013), Kesieme et al. (2013), Loutatidou and Arafat (2015), Ophir and Lokiec (2004), Reddy and Ghaffour (2007), Wittholz et al. (2008), Wade (2001)
Scaling exponent	0.83	Kesieme et al. (2013), Wittholz et al. (2008)
MED Operating Costs		
Plant availability	90%	Al-Sahali and Ettouney (2007), Ettouney et al. (2002), Kesieme et al. (2013), Reddy and Ghaffour (2007), Wade (2001), Wittholz et al. (2008)
electricity cost	$0.05/kWh	Ettouney et al. (2002)
electric power consumption	2.5 kWh/m^3	Al-Sahali and Ettouney (2007), for fluid pumping power
chemical cost	$0.025/$m^3$	Ettouney et al. (2002)
labor cost	$0.1/$m^3$	Ettouney et al. (2002)
spare parts	1% of CAPEX	Al-Sahali and Ettouney (2007)
Economic Parameters		
Plant Life	20 years	Akar and Turchi (2016), Al-Sahali and Ettouney (2007), Loutatidou and Arafat (2015), Mistry and Lienhard (2013), NRC (2008), Wittholz et al. (2008)
Fixed Charge Ratio	0.108	GETEM default input value for legacy FCR based LCOE calculations

As desalination technology has advanced, the costs of both thermal and RO desalination have decreased. This trend is likely to continue as methods of utilizing low cost heat sources are developed and membrane technologies improve. Therefore, for the Exploration De-Risk (improved) scenario a geothermal desalination a cost of \$1.00/m³ is targeted. This cost target is competitive with other desalination technologies that have been deployed in the US. However, in regions with fewer water resources desalination applications with water costs greater than this target value could deploy.

4. Results

Geothermal desalination using MED was analyzed in three case studies. The specific case studies evaluated were (1) a hydrothermal resource in the Business-As-Usual Scenario, (2) a hydrothermal resource in the Exploration De-Risk Scenario, and (3) an EGS resource in the Exploration De-Risk Scenario. In all three case studies the geothermal resource temperature was evaluated over the range of 100°C to 200°C in 25°C increments. The scenario selection determined the GETEM inputs used for determining the geothermal resource capital and operating costs.

The capital and operating costs associated with both the geothermal resource and the MED desalination process were evaluated for each case study. Using these costs it was possible to estimate the levelized cost of heat (LCOH) and the levelized cost of water (LCOW) for the range of temperatures evaluated in each case study. The levelized cost of heat calculation uses the geothermal resource capital and operating costs to determine the amortized unit cost of the heat provided by the geothermal resource (Equation 1, (Turchi et al., 2015)). This calculation is not specific to the MED application and could be used to estimate the cost of the geothermal energy for any process heat application for which the geothermal heat characteristics were suitable.

$$LCOH = \frac{\left(CAPEX_{geothermal}\right) \cdot FCR + \left(OPEX_{geothermal}\right)}{Annual\ thermal\ generation} \tag{1}$$

The levelized cost of water calculation uses the capital and operating costs for both the geothermal resource as well as the MED desalination process to determine the unit cost of the desalinated water product (Equation 2, adapted from (Loutatidou and Arafat, 2015)). The LCOW reported in this analysis is specific to the use of MED technology for each of the geothermal resources considered.

$$LCOW = \frac{\left(CAPEX_{geothermal} + CAPEX_{desal}\right) \cdot FCR + \left(OPEX_{geothermal} + OPEX_{desal}\right)}{Annual\ water\ production} \tag{2}$$

Performance and cost specifications for both the geothermal resource and MED desalination process, in addition to a breakdown of the LCOW cost contributions, are included in Table 2 for the Business-As-Usual Scenario with hydrothermal resources, Table 3 for the Exploration De-Risk Scenario with hydrothermal resources, and Table 4 for the Exploration De-Risk Scenario with EGS resources. Plots of the geothermal resource and MED process cost contributions to the LCOW as a function of geothermal resource temperature are provided for each case study analysis in Figure 3 through Figure 5.

As can be observed from the results presented in Table 2 through Table 4 as well as Figure 3 through Figure 5, the LCOH and LCOW decrease with increasing geothermal resource temperature for all scenarios and resource types evaluated. This is similar to the general trend in which levelized cost of electricity (LCOE) decreases with increasing geothermal resource temperature due to the increase in exergy associated with higher temperature resources (assuming equal development costs and production fluid flow rate for all resources). The higher temperature geothermal resources evaluated in this analysis are therefore most likely to achieve the water purification cost targets listed in Section 3.

In the Business-As-Usual Scenario a hydrothermal resource achieves the reference scenario cost target of $1.50/m³ with resource temperatures of approximately 150°C and greater. A hydrothermal resource in the Exploration De-Risk Scenario achieves the improved scenario cost target of $1.00/m³ with a resource temperature of 200°C (although temperatures above 200°C were not evaluated, it is presumed that the LCOW would follow the observed trend of decreasing cost with increasing resource temperature). Although EGS resources in the Exploration De-Risk Scenario do not achieve the improved scenario target cost of $1.00/m³ at the resource temperatures evaluated, EGS resources have the potential advantage of being deployable at locations where hydrothermal resources do not exist, which would provide much needed flexibility toward meeting the desalination co-location requirements. Ultimately co-location issues, rather than cost targets, are likely to provide the largest barrier to widespread deployment of geothermal energy based desalination processes, and the use of EGS resources in combination with lower cost desalination technologies may be required.

The cost of geothermal heat can also be compared with the cost of heat provided by natural gas combustion, although combustion of natural gas provides heat at a significantly higher exergy which allows for use of a desalination process requiring high-grade heat input and/or cascaded heat use (e.g. power generation and desalination). Nonetheless, a comparison of the cost of geothermal heat versus the cost of steam may be useful in certain circumstances. A review of natural gas prices indicates that $2/MMBtu (0.68¢/$kWh_t$) is a historically low price. In all of the case studies evaluated, geothermal resources with temperatures ≥150°C are able to provide heat at a lower LCOH (T≥125°C for the hydrothermal Exploration De-Risk Scenario), such that use of geothermal heat would not introduce an economic penalty in thermal desalination applications that would otherwise require a fossil energy heat source. Although not considered in this analysis, analysis by Kesieme et al. (2013) indicates that the presence of a carbon tax could further improve the economic viability of a renewable energy based desalination process relative to a fossil energy based process.

5. Discussion

5.1 Limitations and caveats of the technology and/or analysis

The LCOH and LCOW estimates assume that the hydrothermal and EGS resources have the attributes specified in Table 1. Differences in reservoir depth and production fluid flow rate could significantly alter these water purification cost estimates. Further, as previously noted, the LCOW estimates exclude the costs of accessing a saline feed water source, an MED process cooling source, and the disposal of the brine concentrate. The cost associated with each of these requirements is likely to vary widely on a site-by-site basis, and sites where they cannot be

Table 2. Business-As-Usual Scenario with hydrothermal resource

Geothermal Resource					
Resource Temperature (°C)	200	175	150	125	100
reinjection temperature (°C)	70	70	70	70	55
resource depth (m)	1500	1500	1500	1500	1500
No. production wells drilled	3.95	3.95	3.95	3.95	3.95
No. injection wells drilled	2.34	2.34	2.34	2.33	2.33
Avg. distance well to plant (m)	750	750	750	750	750
geothermal pumping power (kW)	2,571	2,613	2,694	2,810	2,946
Geothermal CAPEX					
production well cost	$12,551,000	$12,551,000	$12,551,000	$12,551,000	$12,551,000
injection well cost	$7,437,000	$7,431,000	$7,425,000	$7,421,000	$7,418,000
field gathering system costs	$3,141,000	$3,119,000	$3,102,000	$3,089,000	$3,081,000
GF pump costs	$1,695,000	$1,652,000	$1,639,000	$1,654,000	$1,910,000
indirect costs	$659,000	$651,000	$647,000	$647,000	$681,000
total	$25,484,000	$25,404,000	$25,365,000	$25,362,000	$25,641,000
Geothermal OPEX					
well field maintenance ($/yr)	$353,000	$355,000	$355,000	$356,000	$359,000
pump O&M ($/yr)	$375,000	$332,000	$309,000	$299,000	$298,000
pumping power ($/yr)	$1,014,000	$1,030,000	$1,062,000	$1,108,000	$1,162,000
labor ($/yr)	$137,000	$126,000	$112,000	$95,000	$74,000
MED desalination process					
plant capacity (m^3/day)	49,400	39,600	30,000	20,500	12,800
GOR (kg/kg)	7.24	7.24	7.24	7.24	5.63
specific thermal energy (kWh/m^3)	89.3	89.3	89.3	89.3	116.5
MED process equip CAPEX	$74,191,000	$61,715,000	$48,984,000	$35,747,000	$24,176,000
Geothermal Cost Components					
CAPEX ($/$m^3$)	$0.17	$0.21	$0.28	$0.41	$0.66
well field maintenance ($/$m^3$)	$0.02	$0.03	$0.04	$0.05	$0.09
pump maintenance ($/$m^3$)	$0.02	$0.03	$0.03	$0.04	$0.07
pump power ($/$m^3$)	$0.06	$0.08	$0.11	$0.16	$0.28
well field labor ($/$m^3$)	$0.01	$0.01	$0.01	$0.01	$0.02
subtotal ($/$m^3$)	$0.29	$0.35	$0.46	$0.68	$1.11
MED Process Cost Components					
CAPEX ($/$m^3$)	$0.49	$0.51	$0.54	$0.57	$0.62
electric power ($/$m^3$)	$0.13	$0.13	$0.13	$0.13	$0.13
chemicals ($/$m^3$)	$0.03	$0.03	$0.03	$0.03	$0.03
labor ($/$m^3$)	$0.10	$0.10	$0.10	$0.10	$0.10
spare parts ($/$m^3$)	$0.05	$0.05	$0.05	$0.05	$0.06
subtotal ($/$m^3$)	$0.79	$0.81	$0.84	$0.88	$0.93
Cost Summary					
LCOW ($/$m^3$)	$1.07	$1.16	$1.30	$1.56	$2.04
LCOH (¢/kWh)	0.318	0.393	0.519	0.761	0.949

Table 3. Exploration De-Risk Scenario with hydrothermal resource

Geothermal Resource					
Resource Temperature (°C)	200	175	150	125	100
reinjection temperature (°C)	70	70	70	70	55
resource depth (m)	1500	1500	1500	1500	1500
No. production wells drilled	3.95	3.95	3.95	3.95	3.95
No. injection wells drilled	2.34	2.34	2.34	2.33	2.33
Avg. distance well to plant (m)	750	750	750	750	750
geothermal pumping power (kW)	2,571	2,613	2,694	2,810	2,946
Geothermal CAPEX					
production well cost	$6,507,000	$6,507,000	$6,507,000	$6,507,000	$6,507,000
injection well cost	$3,856,000	$3,852,000	$3,849,000	$3,847,000	$3,845,000
field gathering system costs	$3,141,000	$3,119,000	$3,102,000	$3,089,000	$3,081,000
GF pump costs	$1,695,000	$1,652,000	$1,639,000	$1,654,000	$1,910,000
indirect costs	$659,000	$651,000	$647,000	$647,000	$681,000
total	$15,857,000	$15,781,000	$15,744,000	$15,744,000	$16,024,000
Geothermal OPEX					
well field maintenance ($/yr)	$209,000	$210,000	$211,000	$211,000	$215,000
pump O&M ($/yr)	$375,000	$332,000	$309,000	$299,000	$298,000
pumping power ($/yr)	$1,014,000	$1,030,000	$1,062,000	$1,108,000	$1,162,000
labor ($/yr)	$137,000	$126,000	$112,000	$95,000	$74,000
MED desalination process					
plant capacity (m³/day)	49,400	39,600	30,000	20,500	12,800
GOR (kg/kg)	7.24	7.24	7.24	7.24	5.63
specific thermal energy (kWh/m³)	89.3	89.3	89.3	89.3	116.5
MED process equip CAPEX	$74,191,000	$61,715,000	$48,984,000	$35,747,000	$24,176,000
Geothermal Cost Components					
CAPEX ($/m³)	$0.11	$0.13	$0.17	$0.25	$0.41
well field maintenance ($/m³)	$0.01	$0.02	$0.02	$0.03	$0.05
pump maintenance ($/m³)	$0.02	$0.03	$0.03	$0.04	$0.07
pump power ($/m³)	$0.06	$0.08	$0.11	$0.16	$0.28
well field labor ($/m³)	$0.01	$0.01	$0.01	$0.01	$0.02
subtotal ($/m³)	$0.21	$0.26	$0.34	$0.51	$0.83
MED Process Cost Components					
CAPEX ($/m³)	$0.49	$0.51	$0.54	$0.57	$0.62
electric power ($/m³)	$0.13	$0.13	$0.13	$0.13	$0.13
chemicals ($/m³)	$0.03	$0.03	$0.03	$0.03	$0.03
labor ($/m³)	$0.10	$0.10	$0.10	$0.10	$0.10
spare parts ($/m³)	$0.05	$0.05	$0.05	$0.05	$0.06
subtotal ($/m³)	$0.79	$0.81	$0.84	$0.88	$0.93
Cost Summary					
LCOW ($/m³)	$1.00	$1.07	$1.18	$1.38	$1.76
LCOH (¢/kWh)	0.237	0.292	0.385	0.565	0.708

Table 4. Exploration De-Risk Scenario with EGS resource

Geothermal Resource					
Resource Temperature (°C)	200	175	150	125	100
reinjection temperature (°C)	70	70	70	70	55
resource depth (m)	3800	3300	2800	2300	1800
No. production wells drilled	3.95	3.95	3.95	3.95	3.95
No. injection wells drilled	2.77	2.77	2.77	2.77	2.77
Avg. distance well to plant (m)	500	500	500	500	500
geothermal pumping power (kW)	2,566	3,000	3,465	3,755	3,967
Geothermal CAPEX					
production well cost	$14,672,000	$13,115,000	$11,564,000	$10,022,000	$8,486,000
injection well cost	$10,296,000	$9,203,000	$8,115,000	$7,033,000	$5,955,000
field gathering system costs	$1,392,000	$1,383,000	$1,376,000	$1,371,000	$1,367,000
GF pump costs	$1,715,000	$1,867,000	$2,028,000	$2,129,000	$2,204,000
indirect costs	$424,000	$443,000	$464,000	$477,000	$487,000
total	$28,499,000	$26,011,000	$23,548,000	$21,031,000	$18,500,000
Geothermal OPEX					
well field maintenance ($/yr)	$324,000	$298,000	$273,000	$247,000	$221,000
pump O&M ($/yr)	$247,000	$256,000	$271,000	$283,000	$294,000
pumping power ($/yr)	$1,011,000	$1,183,000	$1,366,000	$1,480,000	$1,564,000
labor ($/yr)	$137,000	$125,000	$111,000	$94,000	$74,000
MED desalination process					
plant capacity (m³/day)	49,400	39,600	30,000	20,500	12,800
GOR (kg/kg)	7.24	7.24	7.24	7.24	5.63
specific thermal energy (kWh/m³)	89.3	89.3	89.3	89.3	116.5
MED process equip CAPEX	$74,191,000	$61,715,000	$48,984,000	$35,747,000	$24,176,000
Geothermal Cost Components					
CAPEX ($/m³)	$0.19	$0.22	$0.26	$0.34	$0.47
well field maintenance ($/m³)	$0.02	$0.02	$0.03	$0.04	$0.05
pump maintenance ($/m³)	$0.02	$0.02	$0.03	$0.04	$0.07
pump power ($/m³)	$0.06	$0.09	$0.14	$0.22	$0.37
well field labor ($/m³)	$0.01	$0.01	$0.01	$0.01	$0.02
subtotal ($/m³)	$0.30	$0.36	$0.46	$0.65	$0.99
MED Process Cost Components					
CAPEX ($/m³)	$0.49	$0.51	$0.54	$0.57	$0.62
electric power ($/m³)	$0.13	$0.13	$0.13	$0.13	$0.13
chemicals ($/m³)	$0.03	$0.03	$0.03	$0.03	$0.03
labor ($/m³)	$0.10	$0.10	$0.10	$0.10	$0.10
spare parts ($/m³)	$0.05	$0.05	$0.05	$0.05	$0.06
subtotal ($/m³)	$0.79	$0.81	$0.84	$0.88	$0.93
Cost Summary					
LCOW ($/m³)	$1.08	$1.17	$1.30	$1.53	$1.91
LCOH (¢/kWh)	0.330	0.401	0.517	0.725	0.845

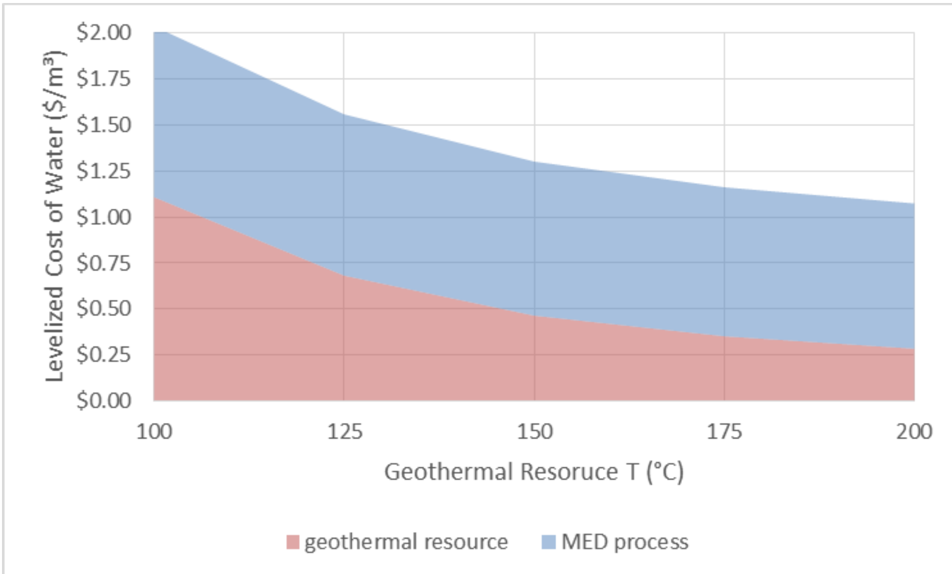

Figure 3. MED Desalination Cost for Hydrothermal Resource in Business-As-Usual Scenario

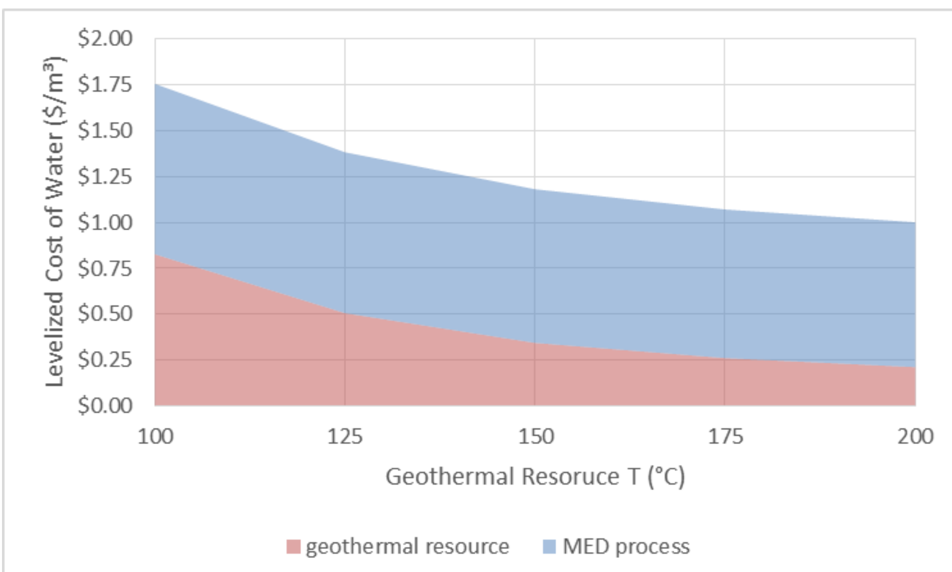

Figure 4. MED Desalination Cost for Hydrothermal Resource in Exploration De-Risk Scenario

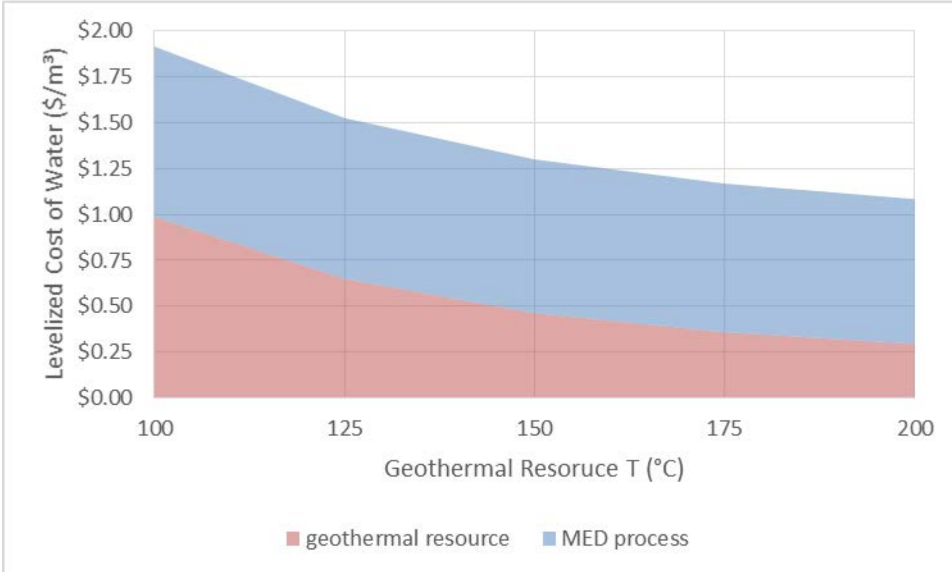

Figure 5. MED Desalination Cost for EGS Resource in Exploration De-Risk Scenario

provided at low cost are not likely suitable candidates for a geothermal energy based desalination project.

As noted in Section 2, there is significant variability in the capital and operating costs reported for MED desalination processes. A chart of MED process cost components for several cost analyses from the literature is presented in Figure 6. In each of the four literature studies compared in Figure 6 there is also variability in the thermal energy cost component. Kesieme et al. (2013) assumes use of low pressure steam at a cost of $0.744/m³ with a total product water cost of $1.48/m³ (costs based on 20,000 m³/day capacity without use of waste heat). Wade (2001) presents a case with an MED cost of $0.953/m³ including thermal energy costs of $0.219/m³ from the use of low pressure steam. Al-Sahali and Ettouney (2007) assume use of low pressure steam extraction from a power plant at a net cost of $0.30/m³. NRC (2008) reports an estimated seawater desalination cost of $0.72/m³ for a 100,000 m³/day MED plant with a thermal energy cost of $0.27/m³. The thermal energy costs in these literature studies can be compared with the geothermal energy cost for the various resource types, temperatures, and scenarios reported as the geothermal cost component subtotal in Table 2, Table 3, and Table 4.

For each of the four literature studies cited, the corresponding product water cost is estimated if geothermal heat at temperatures of 200°C and 150°C were substituted for the thermal energy cost used in each of the original analyses (geothermal energy cost estimates correspond to a hydrothermal resource in Exploration De-Risk Scenario). The results of this exercise are displayed using data series with a diagonal fill pattern in Figure 6. Substitution of heat from a 200°C hydrothermal resource in the Exploration De-Risk Scenario results in lower thermal energy costs than used in any of the cases examined from the literature studies referenced. Substitution of a 150°C hydrothermal resource in the Exploration De-Risk Scenario would result in slightly higher overall product water costs for all of the studies except Kesieme et al, but would nonetheless still result in product water costs of less than the improved scenario cost target of $1.00/m³ if the non-thermal energy cost components from the Al-Sahali & Ettouney or NRC analyses are used.

While this suggests that deployment of cost effective geothermal desalination installations is possible, it also draws attention to the variability of the MED desalination cost estimates available in the literature and highlights that the scaling factor method used in this analysis is not sufficiently accurate for a rigorous determination of the cost effectiveness of a thermal desalination project. Evaluation of the cost effectiveness of a geothermal desalination process will ultimately require use of site- and application- specific operating parameters along with a detailed process design from which all process equipment costs can be determined.

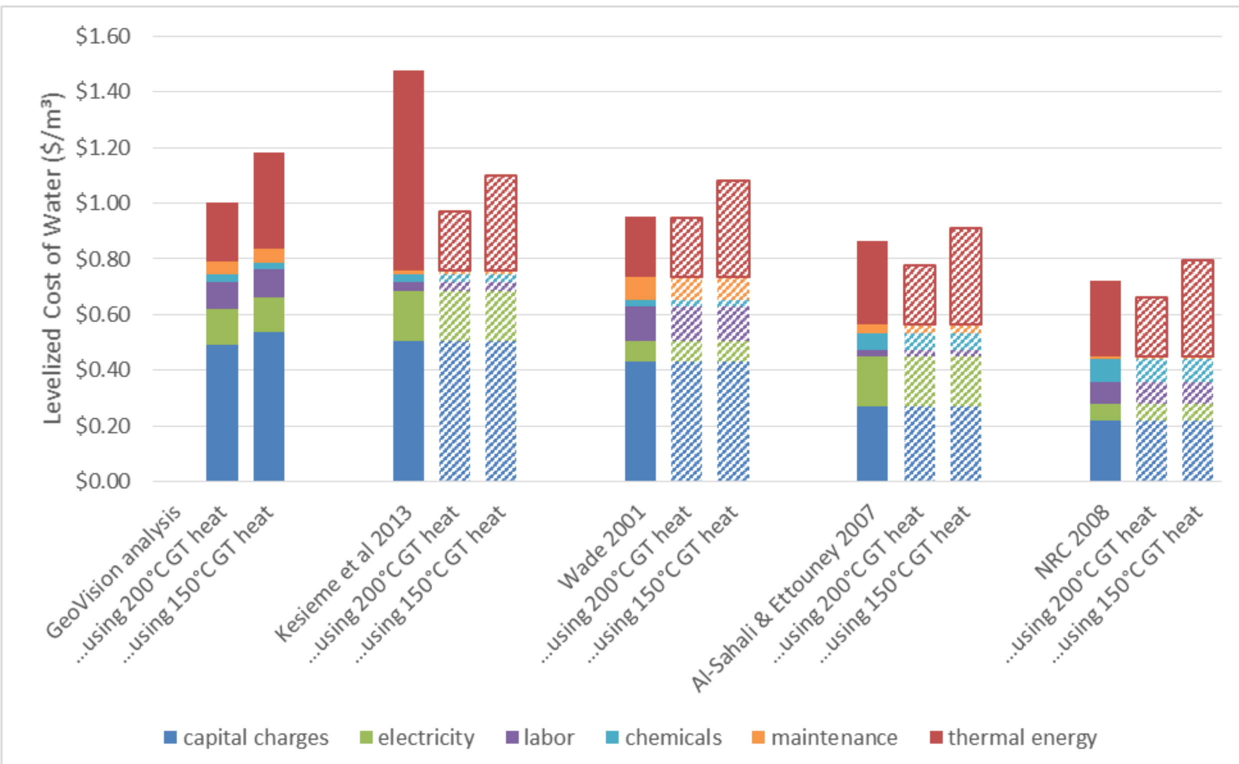

Figure 6. Cost breakdown for several MED thermal desalination cost analyses (Kesieme et al 2013 costs based on 20,000 m³/day capacity without use of waste heat). The second and third columns in each set substitute thermal energy costs corresponding to use of 200°C and 150°C hydrothermal resources in the Exploration De-Risk Scenario.

5.2 Benefits and opportunities for future application

Although Figure 6 suggests that MED-based geothermal desalination processes may be able to achieve the specified cost targets, there is additional flexibility with regard to selection of the desalination technology, especially in the case of higher temperature geothermal resources (T>150°C). When higher temperature geothermal resources are available, an alternate thermal desalination technology may increase performance and/or decrease capital costs such that product water costs lower than those reported in this analysis could be achieved. Alternate thermal desalination technologies include membrane distillation (MD), multi-stage flash (MSF), or hybrid technologies such as MED-MSF or MED with thermal vapor compression (MED-TVC) (Al-Sahali and Ettouney, 2007, Goosen et al., 2010, Nafey et al., 2006, Bundschuh et al., 2015, Veolia Water Solutions & Technologies, Rahimi et al., 2014). Regardless of the thermal desalination technology employed, the LCOH values calculated in Table 2, Table 3, and Table 4 can be used to gauge the cost effectiveness of the specified geothermal heat sources relative to other available heat sources.

Thermal desalination based on the use of MED or another technology may be an appealing use of geothermal heat in the cases in which water production costs meet the specified reference or improved scenario cost targets ($1.50/m³ and $1.00/m³, respectively) such that they would be cost competitive with other water sources. However, if the thermal resource, water source, and water market are not co-located for any given application, it is very unlikely that these cost targets will be achievable.

The most likely near term applications for geothermal desalination involve those in which the geothermal heat source is co-located with a wastewater source that can be treated via desalination to offset water purchase or disposal costs. Two candidate applications include treatment of geothermal power plant cooling tower blowdown water and treatment of co-produced water from oil & gas production operations. Both of these applications are currently being investigated by desalination projects supported by the DOE Geothermal Technologies Office.

Cooling Tower Blowdown Water Treatment

Steam geothermal power plants using closed loop cooling towers are reported to have the highest rate of water consumption of all thermoelectric power generation technologies, estimated as 1,400 gal/MWh (5.3 m³/MWh) (U.S. Department of Energy, 2006). This is primarily due to the relatively low efficiency of geothermal power plants, which is inherent to the low temperature characteristics of geothermal heat sources (in comparison with fossil, nuclear, or solar thermal).

Power plants that use evaporative cooling towers consume water through evaporation, blowdown, and drift. Blowdown is the portion of the recirculated cooling water that must be purged to prevent a buildup in the concentration of impurities. The fraction of water consumed via blowdown is a function of cooling tower operating conditions, especially the number of cycles of concentration. When lower quality water is used as the cooling tower makeup water source, the cooling tower must be operated with a lower number of cycles of concentration (5 cycles is considered a low number of cycles (Cath et al., 2008)) and blowdown can be a significant fraction of the total water consumption (approximately 20% for a cooling tower operating with 5 of cycles of concentration (California Energy Commission, 2003)). The cooling tower blowdown requirements for a geothermal power plant could therefore be as much as 280 gal/MWh (1.1 m³/MWh). A thermal desalination technology can be integrated with the power plant to utilize a fraction of the geothermal energy for treatment of the cooling tower blowdown water. The treated blowdown water could then be reused in the cooling tower, which would have the net effect of decreasing total water consumption while simultaneously reducing blowdown water disposal costs.

Membrane distillation (MD) is a thermal desalination technology that can utilize low grade heat to purify a contaminated feed water stream (Bundschuh et al., 2015, Francis et al., 2014, Goosen et al., 2010, Sarbatly and Chiam, 2013). The National Renewable Energy Laboratory (NREL) and Colorado School of Mines (CSM) are currently working to perform a field demonstration of MD technology for geothermal power plant cooling tower blowdown water treatment (Akar and Turchi, 2016, Turchi et al., 2015). The NREL and CSM project seeks to utilize power plant reinjection fluid to provide the MD process heat requirements.

Due to the large flow rate of injection brine typically available at geothermal power plants, a significant quantity of low-grade heat could be obtained without introducing a large ΔT on the reinjection fluid. Assuming that additional heat can be extracted from the reinjection fluid without violating minimum temperature restrictions (for prevention of geothermal heat exchanger fouling), the only costs associated with this heat source would be any required reinjection piping system modifications and any additional O&M costs associated with pumping the reinjection fluid through the MD heat exchangers. An LCOH estimate for the use of power plant reinjection fluid is provided by Akar and Turchi (2016). The energy harvested from the power plant reinjection water could also be used for purification of water sources other than cooling tower blowdown, such as saline or brackish water sources located nearby candidate geothermal power plants.

Oil & Gas Wastewater Treatment

Every year tens of billions of barrels of co-produced water are brought to the surface as a byproduct of US oil & gas production. The majority of co-produced water from oil & gas production operations is reinjected into the subsurface. Approximately 45% of produced water is reinjected to for enhanced oil recovery (to maintain reservoir pressure) and ~40% is disposed of via injection (Clark and Veil, 2009, Veil, 2015).

There are numerous potential environmental concerns associated with the handling and disposal of produced water from oil & gas operations, including an increasing number of spills from transport operations and earthquakes from injection into deep disposal wells. Additionally, handling and disposal of produced water is a significant operating costs for oil & gas producers. In general, injection disposal costs have been reported to range from \$0.30/bbl (\$1.88/m^3) to as high as \$10.00/bbl (\$62.90/m^3) (Puder and Veil, 2006). Cost effective treatment of the produced water stream could simultaneously decrease environmental risks, offset billions of dollars in annual wastewater disposal costs, and provide an additional source of clean water for subsequent beneficial uses.

The MED process reliability and robustness to fouling make it a suitable option for produced water treatment (Thiel et al., 2015). MED is applicable to all types of water and a wide range of TDS (Igunnu and Chen, 2014), although MED typically achieves a low product water recovery between 20% and 35% (Colorado School of Mines, 2009). Low product water recovery is problematic for applications in which the goal is to reduce the volume of a wastewater stream.

Forward Osmosis (FO) is a semi-permeable membrane-based thermal desalination technology that can achieve high water recovery from concentrated feed streams. These characteristics make FO well suited for the co-produced water treatment application. The Idaho National Laboratory (INL) and Lawrence Berkeley National Laboratory (LBNL) are currently developing forward osmosis based thermal desalination technologies that could utilize geothermal heat for the treatment of co-produced water. The Switchable Polarity Solvent Forward Osmosis (SPS FO) desalination process requires a heat source of 80°C or greater to regenerate the FO draw solution (Wendt et al., 2016, Wendt et al., 2015). An analysis by Augustine and Falkenstern indicates that there are greater than 4 billion barrels per year (~600 million m^3/yr) of produced water with an estimated temperature greater than 80°C (Augustine and Falkenstern, 2014). The co-produced water could therefore serve as both the feed water source as well as the geothermal energy source for the thermal desalination process. Techno-economic analysis of the SPS FO process estimates water treatment costs of \$3.44/m^3 (Wendt et al., 2016). Assuming 80% water recovery from the SPS FO process and a cost of \$1.00/bbl (\$6.3/m^3) for injection disposal of the co-produced water concentrate results in a total water management (treatment plus disposal) cost of \$4.00/m^3, which is considerably less than the typical \$1.00/bbl (\$6.3/m^3) cost of deep injection disposal of the full co-produced water volume. This suggests that there could be potential for significant deployment of geothermal desalination technology for the treatment of co-produced water.

5.3 Conclusions

In conclusion, the conditions for which geothermal energy based desalination projects will be cost effective are highly site- and application-specific.

- Geothermal resource characteristics are highly variable and the resource characteristics evaluated in this analysis are likely representative for only a small fraction of potential sites
- Desalination requirements are similarly highly variable with differences in the feed water quality and the regional costs of pure water; demand may vary seasonally or annually (due to presence or absence of drought conditions), which further complicates the assessment of the long term viability and applicability of a particular project
- Co-location of resources is a major issue; applications that have the greatest potential for near-term deployment are those where the feed source is a wastewater stream (associated with a geothermal heat source or application) that would otherwise require costly treatment and/or disposal.

In the Business-As-Usual Scenario a hydrothermal resource achieves the reference scenario cost target of \$1.50/m^3 with resource temperatures of approximately 150°C and greater. A hydrothermal resource in the Exploration De-Risk Scenario achieves the improved scenario cost target of \$1.00/m^3 with a resource temperature of 200°C. Although EGS resources in the Exploration De-Risk Scenario do not achieve the improved scenario target cost of \$1.00/m^3 at the resource temperatures evaluated, EGS resources have the potential advantage of being deployable at locations where hydrothermal resources do not exist, which would provide much needed flexibility toward meeting the desalination co-location requirements. Ultimately co-location issues, rather than cost targets, are likely to provide the largest barrier to widespread deployment of geothermal energy based desalination processes, and the use of EGS resources in combination with lower cost desalination technologies may be required.

In addition to applications where resources are naturally co-located, applications where desalination can decrease the volume of water that must be treated or disposed of at a higher cost are most likely to provide sufficient economic benefit to favor deployment. Specific wastewater treatment applications in which geothermal heat is inherently available include the treatment of geothermal power plant cooling tower blowdown water, and treatment of thermally active co-produced water from oil & gas production operations.

In applications where the primary driver for installation of a desalination plant are the demand for purified water, geothermal energy based desalination is expected to be most cost-competitive when using higher temperature geothermal resources, and the cost competitiveness would further increase if the geothermal energy was used in a thermal desalination process with improved performance and/or lower costs relative to the MED baseline desalination process evaluated in this analysis.

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