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Technical Report
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Preface

This report compiles and summarizes the results for Project 2.5.1.1, "Low-Enthalpy Geothermal Desalination," that were submitted to the DOE Geothermal Technologies Office in milestone reports throughout fiscal year 2015.

Acknowledgements

This work is a collaborative research project between NREL and researchers in the Advanced Water Technology Center (AQWATEC) at the Colorado School of Mines (CSM) in Golden, Colorado. The CSM team is led by Dr. Tzahi Cath and includes Dr. Johan Vanneste, Dr. Mengistu Geza, and Ms. Bethany Grace Yaffe.

Thanks are given to Science Undergraduate Laboratory Intern (SULI) Jeremy Poe for his investigation of cooling-tower blowdown water sources in 2015.

Nomenclature or List of Acronyms

AGMD	Air-gap membrane distillation
AQWATEC	Advanced Water Technology Center
BWRO	Brackish-water reverse osmosis
CSM	Colorado School of Mines
DST	Decision Support Tool
DOE	U.S. Department of Energy
FCR	Fixed charge rate
GAC	Granular activated carbon
GDsalt	Geothermal Desalination support Tool
GTO	Geothermal Technologies Office
GUI	Graphical user interface
IX	Ion exchange
MED	Multi-effect distillation
MGD	Million gallons per day
MVC	Mechanical vapor compression
NF	Nanofiltration
NREL	National Renewable Energy Laboratory
O&M	Operating and maintenance
ORC	Organic Rankine cycle
RO	Reverse osmosis
SAM	System Advisor Model
SWRO	Seawater reverse osmosis
TDS	Total dissolved solids
TSS	Total suspended solids
TVC	Thermal vapor compression
USGS	United States Geological Survey
VMD	Vacuum membrane distillation

Executive Summary

Based on geothermal resource assessment estimates by the U.S. Geological Survey (USGS), total resource capacity for identified hydrothermal systems having mean reservoir temperature between 50°C and 90°C is over 9,800 MW_{th}. The USGS is revisiting this assessment, and an updated version anticipated in late 2015 or 2016. Recent presentations by the USGS indicate that the estimated capacity will increase. In total, 13 states have potential for low-temperature hydrothermal resources—with Idaho, Nevada, Arizona, California, and Utah ranking as the highest potential. These areas also overlap with locations of water scarcity and stress.

This joint project between the National Renewable Energy Laboratory and the Colorado School of Mines (CSM) has examined the potential of using low-temperature geothermal resources for desalination. The temperature range in question is not well suited for electricity generation, but can be used for direct heating. Accordingly, the best integration approaches use thermal desalination technologies such as multi-effect distillation (MED) or membrane distillation (MD), rather than electric-driven technologies such as reverse osmosis (RO).

The team developed a decision support tool to assist with the assessment of geothermal-driven desalination. This tool, named "GDsalt," was built on prior work at CSM's Advanced Water Technology Center. The examination of different desalination technologies led to the selection of MD for pairing with geothermal energy. MD operates at near-ambient pressure and temperatures less than 100°C with hydrophobic membranes. The technology is modular like RO, but the equipment costs are lower. The thermal energy demands of MD are higher than MED, but this is offset by an ability to run at lower temperatures and a low capital cost. Consequently, a geothermal-MD system could offer a low capital cost and, if paired with low-cost geothermal energy, a low operating cost. The integration of geothermal energy and MD is believed to be capable of achieving a product water cost of less than $1.5 per cubic meter.

The economics of desalination remain challenging regardless of technology. For example, 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. Product water from the new Carlsbad Desalination Project, a large RO plant in southern California, is expected to cost about \$1.7/m^3, which is stated to be about twice the cost of alternative water sources. Consequently, desalination is best applied where high-quality product water is valued and the impaired source water requires treatment for disposal. Such a situation provides two sources of "revenue" for the process—valuable product water and avoided treatment costs. The deployment of desalination as a hedge against future water scarcity, despite its relative cost, is sometimes listed as an additional supporting factor.

Based on these considerations, the treatment of cooling-tower blowdown water has been selected as an appealing application for demonstration of geothermal-MD and a potential site has been identified. A proposed field-test project will access cooling-tower blowdown water at a geothermal power plant and use geothermal heat in a small-scale MD process. Objectives include the following:

- Demonstrate the integration of MD with geothermal energy,

- Develop a performance model and validate membrane flux estimates with commercial-scale modules under field conditions at different operating conditions,
- Demonstrate long-term life and performance of the membranes and membrane modules,
- Test and evaluate antiscaling and/or antifouling coatings applied to commercial membranes, and
- Estimate cost of product water based on membrane performance and a sensitivity analysis to the cost of geothermal heat. Define conditions that lead to costs of less than \$1.5/m^3 or otherwise provide economic viability. Describe and quantify applications beneficial to the geothermal industry.

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1 Background and Motivation

Geothermal resources are primarily located in the western United States and are often divided into high-temperature and low-temperature resources. In general, high-temperature resources are suitable for power generation at utility scale (i.e., >5 MW). At the low-temperature end of the spectrum, e.g., less than about 100°C, resources may be suitable for small-scale power generation, but are more readily useful for direct-use applications (e.g., space heating, greenhouses). The low-temperature resource base is more widely distributed and is also highly underutilized. Therefore, finding alternative uses for the low-temperature resource base—beyond small-scale, distributed power generation and typical direct-use applications—is important to the adoption of geothermal energy as a long-term, sustainable option in the U.S. energy portfolio. Ultimately, this is the impetus of this study.

The desalination of impaired waters is a potentially useful application of low-enthalpy geothermal energy, for example, from low-temperature resources or rejected heat from high-temperature geothermal power plants. Desalination, and more specifically thermal desalination, is one potential direct-use application of low-temperature geothermal energy sources. A viable geothermal desalination application must meet several criteria:

1. Have an available source of geothermal energy at low cost.

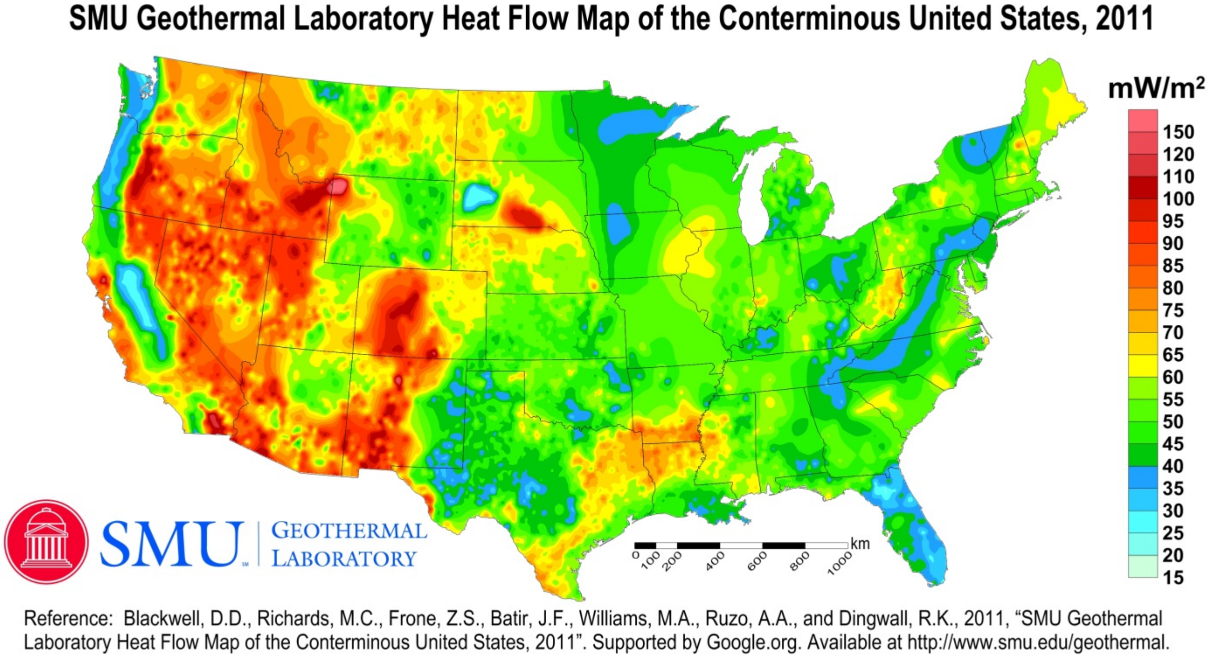
2. Have impaired source water that can be processed via one or more pretreatment and desalination processes to create a beneficial product water. Potential source waters include: brackish surface or groundwater, seawater, brines co-produced from oil and gas operations, industrial wastewater, and agriculture drainage water. In some instances, the geothermal brine itself could be used as the source water.

3. Have a suitable user or market for the product water to justify the investment and operating costs.

Substantial declines in potable groundwater have been observed across the United States in the past decade [1]. Along with water conservation measures, desalination is gaining attention throughout the United States as an alternative fresh-water source to hedge against future drought and water shortages due to population growth, weather patterns, and climate change. In the West, many of the aquifers experiencing the highest declines are situated in areas where geothermal resources coexist (Figure 1). Additionally, a number of these areas are collocated with impaired waters (Figure 2).

The concept explored in this study is that heat from low-enthalpy geothermal sources can be directly used in thermal desalination processes. This project evaluated the technical feasibility of combining desalination technology with available low-enthalpy heat to produce high-quality water that would be of beneficial use for local consumers. This report covers progress that occurred on the project during FY14 and FY15.

The project was undertaken as a collaborative effort between the National Renewable Energy Laboratory (NREL) and researchers within the Advanced Water Technology Center (AQWATEC) at the Colorado School of Mines (CSM) in Golden, Colorado.


SMU Geothermal Laboratory Heat Flow Map of the Conterminous United States, 2011

Reference: Blackwell, D.D., Richards, M.C., Frone, Z.S., Batir, J.F., Williams, M.A., Ruzo, A.A., and Dingwall, R.K., 2011, "SMU Geothermal Laboratory Heat Flow Map of the Conterminous United States, 2011". Supported by Google.org. Available at http://www.smu.edu/geothermal.

Figure 1. Geothermal resource potential based on Southern Methodist University Heat Flow map.

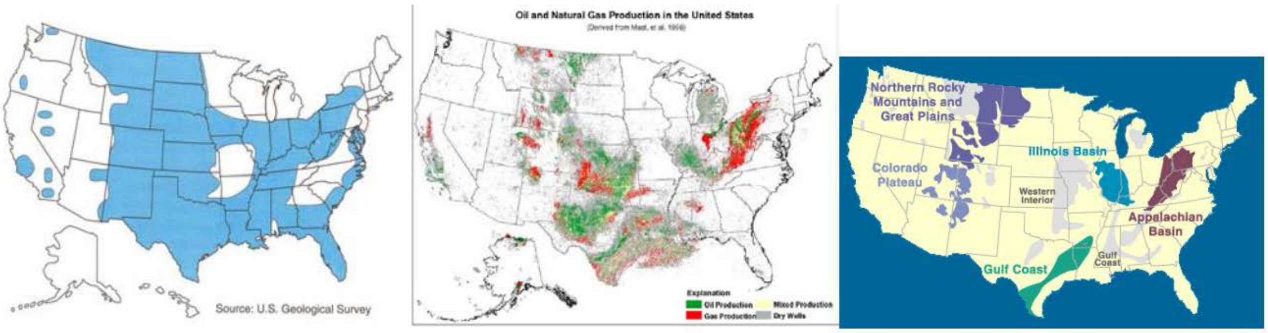


Figure 2. Location and extent of saline aquifers, oil and natural gas production, and coalbed methane reserves; all could be sources of impaired waters [2].

2 Project Tasks

The goal of the project was to provide the U.S. Department of Energy's (DOE's) Geothermal Technologies Office (GTO) with insight on the potential impacts and technology challenges related to geothermal-assisted desalination. The data collected and tools developed in the project will also be valuable to stakeholders, allowing them to identify efficient and suitable desalination processes based on site-specific constraints. Outcomes of this project include:

- Adaptation of an existing decision support tool capable of identifying suitable treatment trains (i.e., desalination and pretreatment processes) based on impaired water quality, the type and quantity of energy needed for desalination, and desired water quality for beneficial use;
- Identification of collocated geothermal and impaired water resources that could meet the identified energy demand;
- Conceptual designs and thermal analysis of the integration of geothermal and desalination technologies for selected sites;
- Identification of candidate sites for a demonstration project; and,
- An engineering gap assessment to determine if further research and development (R&D) is required before this concept can be adopted.

The project was divided into five tasks, as described next.

Task 1 – Brine characterization and site selection

Water chemistry data for impaired waters were collected and analyzed to determine water type (i.e., classification) using a standard approach used by the groundwater industry. The data were then analyzed to determine a reasonable subset of locations that will be used throughout the rest of the study. Water-quality data were used as an input to Task 3. This task was completed in December 2013. The results were documented in a November 2014 milestone report to DOE and are reviewed in Appendix C.

Task 2 – Decision support tool refinement

An existing decision support tool developed by CSM was modified to incorporate the inputs necessary to complete the geothermal desalination screening selection task. The tool already contained information regarding current desalination technologies and pretreatment processes that allow it to calculate product water quality based on source water chemistry and treatment method. New inputs included the results of the brine characterization task and resource temperature for the selected site. The tool outputs suggested desalination technologies (and pretreatment processes) that can be used for given source water and the energy (heat and electricity) required to complete the desalination process. The revised tool has been designated as the geothermal desalination support tool or "GDsalt."

Task 3 – Screening analysis

The screening analysis used GDsalt to determine if selected sites were viable options for adoption of geothermal desalination technology. The screening analysis focused on geothermal sites that were collocated with impaired water, whether it be surface or groundwater, seawater, or geothermal and/or co-produced brines. The screening analysis also considered desired beneficial use (which is a GDsalt input), because if a user needs certain water but the technology cannot provide it given the input water type/quality, then the site would be eliminated from consideration for potential demonstration. The screening analysis identified the best desalination options for integration with low-temperature geothermal energy.

Task 4 – Conceptual design and economic analysis

After the sites were screened and the most promising technologies identified, a conceptual design was developed for representative locations. This task objective was pursued through a relationship with the senior design course instructors in the Chemical & Biological Engineering Department at CSM. An example geothermal-desalination demonstration plant was modeled by the senior design class using Aspen simulation software to estimate the system performance and cost. NREL and the GDsalt team mentored the senior design project team to provide context for the project. The completed class project helped test and validate GDsalt.

Task 5 – Demonstration requirements

The identification of requirements for geothermal desalination was followed by locating a potential test site for a field demonstration. This demonstration was proposed as follow-on work under the FY16 “Lab Call” research solicitation from the GTO.

3 GDsalt Decision Support Tool

Selection of water desalination processes is a complex task, and it can include assessment of dozens of desalination and pretreatment technologies [3]. It involves developing a treatment train that comprises a desalination technology and pretreatment processes (in both cases, there can be one or more technologies) based on input water quality and quantity and the target end-use quality. A computerized decision support tool is a good way to "automate" this process to identify the best candidate treatment train(s) based on user-defined inputs such as water quality, treatment efficiency, energy type available, energy demand limitations, and overall economics (i.e., capital and operations and maintenance (O&M) costs). The objective of the GDsalt tool developed as part of this study was to identify suitable treatment trains based on input water quality and quantity, intended use of the treated water (beneficial use), and geothermal resource capacity, as specified by the user. GDsalt is not meant to replace an engineering design—it is a broad estimation tool that suggests one or more reasonable treatment trains that would meet the user's main requirements. If the user wishes to pursue one of the suggested options, the next step would be a more detailed engineering assessment.

3.1 GDsalt Framework

GDsalt's objective function includes monetary and non-monetary objectives. The monetary objectives include the total capital cost and annual O&M costs. Initial capital costs of investment and O&M costs for each treatment technology are calculated based on other inputs such as plant size and chemical demand. The tool also accounts for non-monetary objectives using a user- and expert-ranking approach that allows users to enter weightings regarding each treatment method with respect to a list of non-monetary criteria such as footprint, modularity, or skill requirement. The monetary and non-monetary criteria are finally combined into a single objective function. GDsalt determines suitable treatment trains in terms of the user-defined objectives while meeting target water-quality constraints. A conceptual representation of GDsalt is provided in Figure 3; more detail is provided in Appendix A.

Figure 3. Conceptual framework for selecting a treatment train. Modifications to the pre-existing CSM decision support tool are highlighted in green.

Several constraints have to be met by GDsalt during the treatment technology selection process. One of the constraints is achieving the water-quality requirements for the intended beneficial use as defined by established water-quality standards. Based on feedwater quality and target water requirements, the tool calculates the constituents requiring removal and the level of required treatment. The tool can access a built-in database of feedwater quality for different source water types or allow users to input their own water-quality data. The tool's database also includes the level of treatment required for each beneficial-use category. The graphical user interface (GUI) allows the user to select source water-type and targeted beneficial-use category. The beneficial-use options include: potable water, livestock watering, industrial, commercial, agricultural irrigation, fisheries and wildlife maintenance and enhancement, recreation, fire protection, dust suppression, and more. Other constraints that affect the selection of treatment technologies are also included in GDsalt. These include the ability for the user to include or exclude specific treatment technologies based on site-specific conditions and allowing GDsalt to optimize additional technologies that are required. Constraints can also be defined to limit the use of certain technologies based on source-water type or type of energy source for desalination. In this fashion, one can configure GDsalt to favor technologies that work best with the geothermal resource in question.

3.2 Developing GDsalt

This study upgraded and modified a tool developed by CSM that was originally used to investigate treatment of produced water from coalbed methane operations [3]. The basic decision support tool comprises four modules: 1) Water Quality, 2) Treatment Selection, 3) Beneficial Use, and 4) Economics. This existing tool lacked the ability to determine and optimize energy source (heat and/or electricity) necessary to treat a given input water type to the desired beneficial use, as well as the ability to optimize the treatment train selection around several objective functions and constraints. Therefore, a number of modifications were made to address these issues in the new geothermal desalination support tool (GDsalt). The primary changes are outlined in Table 1.

Table 1. GDsalt Module description with changes made to the original CSM tool

Module	Original Support Tool	GDsalt Modifications
Source Water Quality	• Location, chemical constituent, and flow rate data for select hydrocarbon resources	• Same data parameters but for groundwater, surface water, seawater, and produced water located near geothermal resources
Treatment Selection	• 32 desalination technologies and associated pretreatment processes • All of the technologies included in GDsalt are commercially available and the processes thoroughly vetted [3]. • Expert ranking that can be user defined; default emphasis was on cost and treatment efficiency	• Updates to expert ranking process within the tool to account for energy-demand module • Integration of the optimization model to improve decision process and allow fewer assumptions about user-specified inputs
Beneficial Use	• Drinking, livestock, agriculture, and industrial water-quality requirements	• None

Module	Original Support Tool	GDsalt Modifications
Economics	- Capital and O&M cost information for the various desalination and pretreatment technologies	- Updated capital and O&M cost information
Energy Demand	- Did not exist	- Specify energy type (electricity and heat) and demand

3.3 Energy Module

A key change in GDsalt was calculating the amount of energy (heat and electricity) required to complete the pretreatment and desalination processes based on input water quantity and quality, treatment efficiency, and desired beneficial use. This energy demand can be compared directly with the collocated geothermal resource capacity (electricity or thermal energy) to determine if the geothermal energy can meet the demand.

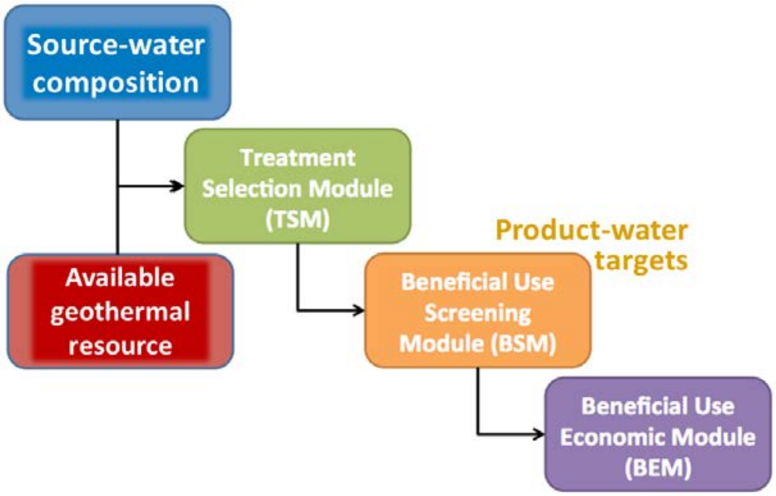


Figure 4. Module data flow for optimization of a treatment train in GDsalt.

3.4 Optimization Model

The other major modification to GDsalt was addition of an optimization model to the decision process (green box in Figure 3). As stated above, selection of treatment technologies is influenced by several criteria, both monetary and non-monetary. Thus, the treatment selection was approached by combining these criteria into a single “objective function” and approaching the solution as an optimization problem. This method allowed inclusion of multiple criteria and can be applied with one or more constraints. Multi-objective optimization techniques can resolve conflicting objectives (such as low installed cost vs. low life-cycle cost), which may require a trade-off between different objectives. In this study, we introduced multiple monetary and non-monetary criteria (see Appendix A). The non-monetary criteria were assigned numerical weighting values based on default or user-defined scores. For example, a treatment technology may have relatively low capital and O&M costs, but may require a larger footprint than desired or special operator skills that are scarce.

When dealing with multiple conflicting objectives, the solution can be seen as optimal when no objective value can be improved without impairing some other objective. Converting individual objectives into a single objective function allows the problem to be solved by minimizing or maximizing this function. When the objectives included in the multi-objective problem are both quantitative and qualitative, normalization is needed. The weighted-sum method allows the multi-objective optimization problem to be cast as a single-objective mathematical optimization problem. This single-objective function was constructed as a sum of objective functions multiplied by weighting coefficients. Weights were applied by the user to each criterion based on AQWATEC's professional judgment regarding the importance of each objective to the decision making. A criterion can be totally excluded if the user assigns a score of zero. Thus, one or many of the criteria summarized in Tables A1 and A2 can be used in the selection process.

Other modifications and updates were made to the original modules to improve the performance of GDsalt and the precision of results. These include: ability for the user to include or exclude a pretreatment process or a desalination technology based on site-specific needs, modification to use quantitative values for criteria that can be quantified (e.g., capital, O&M cost, energy demand), flexibility to use a single criterion (e.g., energy demand or cost), or a combination of multiple criteria, and improvements in the user interface.

3.5 Treatment-Train Selection Methodology

GDsalt is intended to select suitable treatment trains with respect to monetary and non-monetary criteria while meeting the water-quality requirements and other constraints. The following section lists some of the components available within GDsalt.

Desalination Technologies

GDsalt includes several desalination technologies; the major types are listed in Table 2. The preferred desalination process is selected using the optimization procedure. Total dissolved solids (TDS) concentration is used for preliminary screening of the desalination processes. TDS is the amount of dissolved inorganic and organic constituents in water and is also referred to as salinity. In this module, TDS is calculated based on the summation of ions present in the water; however, in most cases, TDS can also be estimated based on the electrical conductivity of a water sample. The constraint is defined such that the salts are removed to the level required by the beneficial use. In some cases, where the TDS is very low, the tool will point out that desalination is not required and will provide an alternative list of technologies to deal with specific contaminants that may exceed water standards.

Table 2. Basic desalination technologies included in GDsalt

Desalination Technology	Electric Energy Required	Thermal Energy Required
Electrodialysis	✓	
Membrane distillation	✓	✓
Thermal distillation	✓	✓
FO-RO hybrid (hybrid of forward osmosis and reverse osmosis)	✓	
FO-thermal (hybrid of thermal distillation and forward osmosis)	✓	✓
Tight nanofiltration	✓	

Desalination Technology	**Electric Energy Required**	**Thermal Energy Required**
Loose nanofiltration	✓	
Brackish-water reverse osmosis	✓	
Seawater reverse osmosis	✓	
Dewvaporation, aka humidification-dehumidification desalination	✓	
Multi-effect humidification	✓	✓
Mechanical vapor compression	✓	
Thermal vapor compression	✓	✓
Multi-stage flash	✓	✓
Multi-effect distillation	✓	✓

Beneficial-Use Criteria

Several beneficial-use categories are included in GDsalt, which include potable use, livestock watering, crop irrigation, environmental restoration, and surface water discharge (see Appendix B). Two beneficial-use options were considered in the testing: potable use and crop irrigation. Target water-quality standards for the different beneficial-use categories are built into GDsalt. For drinking water, the U.S. Environmental Protection Agency (EPA) standards for drinking water quality are used [4]. The United Nations Food and Agriculture Organization water-quality criteria for irrigation were used for crop irrigation beneficial-use category [5].

Impact of Contaminants

GDsalt's source water database has a list of contaminants and constituents in a range of source waters (alternatively the user can input their own water quality data). Contaminants requiring removal are selected based on their concentration in the source water and target concentration levels required for the selected beneficial use. If the concentration of a constituent in the source water is above the limit or guideline required by the beneficial use, the contaminant is relevant in the selection of treatment methods. If the concentration of a constituent is above the limit required to protect membranes or other processes, a pretreatment process will be selected. The model outputs the list of constituents that require removal.

Protecting the treatment train from damage from source water constituents (e.g., fouling or mineral scaling) is required. Potential damage is partially a function of treatment efficiency, which is calculated using the Total Flux and Scalant methodology [6]. The methodology in GDsalt calculates the solubility index for both the source water and concentrate streams, and returns the ionic concentration and the scaling index of each stream. If the concentration of a constituent is above the limit required for protecting membranes or other processes from scaling, the contaminant is considered relevant in the selection of treatment methods, and GDsalt identifies pretreatment technologies necessary to protect membranes or heat exchanger surfaces before the source water flows to the desalination step.

Expert Ranking Criteria

The inclusion of a criteria ranking system allows the user to weight certain selection criteria and can be used to favor technologies that meet certain requirements—for example, compatibility with geothermal heat sources. The selection of a treatment train is based on the attributes of the treatment technologies with respect to a range of criteria such as rejection/removal capability of specific constituents by each process, ability to automate, operator skill level, flexibility, footprint, industrial status, chemical demand, energy demand, mobility, modularity, and relative capital cost. This is done by using a 5-point scale, where "5" indicates that the criterion is not favored and "1" indicates that the criterion is preferable. A criterion can be completely excluded if the user assigns a score of zero. This makes the tool more flexible by allowing the user to choose one or more criteria relevant to specific conditions.

Treatment Efficiency

Achieving the required treatment efficiency is a hard constraint. GDsalt will select a combination of most desirable technologies with respect to monetary and non-monetary criteria while achieving the target water-quality requirements for the selected beneficial use. Treatment efficiency, R, is defined as the percent rejection or removal of a specific constituent:

$$R = \left(\frac{C_{feed} - C_{product}}{C_{feed}}\right) * 100\%$$

User Preference

GDsalt allows users to include or exclude treatment technologies from consideration, depending on their specific situation. The tool selects a combination of suitable treatment technologies with respect to technical and economic criteria; however, users may want to include or exclude specific treatment technologies.

Pretreatment

Pretreatment is carried out before desalination to protect elements of the desalination process, such as RO membranes [6]. This constraint is particularly important for some metals such as arsenic, barium, calcium, magnesium, and silica that may precipitate and cause crystallization and scaling. Removal of suspended solids is another common pretreatment requirement.

GDsalt Output

The primary output from GDsalt is one or more treatment train(s) that meet the treatment goals. In addition, GDsalt outputs the list of contaminants requiring removal, capital cost, annual O&M cost, and electrical and thermal energy requirements. Although the treatment trains are listed in ranked order based on their composite score, it should be noted that some choices may not be significantly different from the other choices within the level of fidelity provided by the GDsalt analysis. The listed trains should be considered *suitable* options by the user, and user experience can be used to down-select from within the provided candidates.

3.6 Testing GDsalt

Organized testing of the GDsalt decision support tool was undertaken by a senior design class within the chemical engineering department at CSM. The class consisted of several teams composed of five seniors. The NREL team drafted a geothermal-desalination case study (see Appendix D) that was presented to the class as an analysis option. Five teams selected this case study for their project. The student groups were presented a series of source waters (Table 3) that required desalination prior to beneficial use of the water. The student groups were asked to design two separate treatment trains for two potential beneficial uses: potable reuse and crop irrigation. The water-quality requirements for the two beneficial uses are included in Table 4. They used GDsalt to choose a treatment train for their chosen source waters, comparing the resulting treatment trains for each of the beneficial-use applications. Following this application of the tool, the student groups were asked to suggest improvements or adjustments to the tool based on their experience with its use.

Table 3. Water chemistry of potential source waters

Constituent List	Unit	CA Salton Sea surface water	CA New River surface water	TX Hidalgo County groundwater	TX Gulf coast seawater	TX Hidalgo County produced water
Alkalinity-Bicarbonate	mg/L	245.0	300.0	563.8	171.0	77.6
Alkalinity-Carbonate	mg/L	2.0		-	3.0	-
Ammonia	mg/L	1.2	3.6	-	-	-
Barium	mg/L	-		-	0.1	4.0
Boron	mg/L	11.1	0.9	-	7.8	-
Calcium	mg/L	944.0	177.0	113.0	386.0	3,602.5
Chloride	mg/L	17,240.0	724.0	1,860.0	17,083.0	14,467.5
Fluoride	mg/L	2.1	1.8	3.5	-	-
Iron (II)	mg/L	-		-	4.7	261.7
Magnesium	mg/L	1,400.0	82.8	105.0	1,135.0	83.0
Nitrate (as N)	mg/L	-		5.6	-	-
o-Phosphate	mg/L	0.0	0.7	-	-	-
pH	pH	-		7.9	-	-
Potassium	mg/L	258.0	12.6	26.4	487.0	244.6
Silica (SiO_2)	mg/L	4.6	7.3	60.1	24.0	-
Silver	mg/L	-		-	-	-
Sodium	SAR	12,368.0	566.0	1,580.0	8,468.0	5,005.9
Specific Conductance	mg/L	-		5,901.0	-	-
Strontium	mg/L	22.0	3.2	-	5.7	-
Strontium-90	mg/L	-		-	-	-
Sulfate	mg/L	10,500.0	716.0	1,320.0	2,642.0	77.8
TDS (calc)	mg/L	44,087	2,440	5,359	30,515	23,591
Temperature	degC	14 to 36	12 to 30	20.0	14 to 30	40.0
Total Nitrogen (as N)	mg/L	-	4.7	-	-	-
Total Suspended Solids (TSS)	mg/L	36.6	210.0	40.0		40.0
Turbidity	NTU	-		-	5.0	-

Table 4. Water-quality requirements for selected beneficial uses

Component	Units	Potable use	Crop irrigation, non-potable use
Aluminum	mg/L	0.200	5.000
Ammonia	mg/L	0.000	0.000
Arsenic (III)	mg/L	0.010	0.100
Arsenic (V)	mg/L	0.010	0.100
Barium	mg/L	2.000	-
Benzene	mg/L	0.005	-
Beryllium	mg/L	0.004	-
Cadmium	mg/L	0.005	-
Chloride	mg/L	250.000	70.000
Chlorobenzene	mg/L	0.100	-
Chromium, total	mg/L	0.100	0.100
Copper	mg/L	1.300	1.300
Cyanide	mg/L	0.200	-
Ethylbenzene	mg/L	0.700	-
Ethylene Dibromide	mg/L	0.000	-
Fluoride	mg/L	2.000	1.000
Iron (II)	mg/L	0.300	5.000
Iron (III)	mg/L	0.300	5.000
Lead	mg/L	0.015	5.000
Lithium	mg/L	-	15.000
Manganese	mg/L	0.050	0.200
Mercury	mg/L	0.002	-
Nickel	mg/L	-	0.200
Nitrate (as N)	mg/L	10.000	10.000
Nitrite (as N)	mg/L	1.000	1.000
Radioactivity, Gross Beta	pCi/L	15.000	-
Radium-226 + Radium-228	pCi/L	4.000	-
Rd 226+222+228	pCi/L	5.000	-
Selenate	mg/L	0.050	0.020
Silver	mg/L	0.100	-
TDS (calc)	mg/L	500.000	1500.000
Thallium, total	mg/L	0.002	-
Total Suspended Solids (TSS)	mg/L	30.000	30.000
Uranium	µg/L	30.000	-
Xylenes (total)	mg/L	10.000	-
Zinc	mg/L	5.000	-

After the test runs of GDsalt were completed, each group provided suggestions or changes to the GDsalt program in order to increase the usability. The suggested changes fell within the following categories:

- Data input,

- Transparency of background calculations and results,
- Energy cost estimations of thermal distillation technologies,
- Improvements to the GUI, and
- Errors and questions encountered during the runs.

Several groups faced difficulties relating to the tool reverting to default settings upon closing the program. This default caused problems for comparing results, increased the time for using the program through redundancy, and increased the possibility of error. The recommendation was made to save the initial inputs after each test and restore default values to the interface only when the user selects this option. Another suggestion was a two-way GUI that shows the currently set values for each section, or an input sheet that includes the data as they were input by the user.

Another difficulty faced in the program was the lack of clarity in the calculations and default values, as well as in the results of the GDsalt runs. Background calculations were difficult to find by the user, and the detailed results section of the program was confusing and difficult to navigate. The groups suggested more detailed labeling and documentation of the background calculations, variables, and constants, as well as a more clearly defined results section that goes beyond the current initial summary table.

The groups encountered many issues regarding the energy use and cost calculations within the program. These issues included the inability of the program to differentiate between increasing percent recoveries, and the overestimation of required energy and the cost of this energy. Because the energy used in these processes largely determines the O&M costs, it is imperative to have accurate cost estimations to ensure correct selection of the treatment trains. Furthermore, the capital costs were perceived to be underestimated due to the exclusion of some heat-transfer equipment. The suggestion was made that multiple energy-cost levels in economic inputs (i.e., one unit cost for the geothermal energy input and another for any additional heat energy required) would allow for more accurate cost estimations, especially in the case of an energy deficit. Again, the groups asked for more clarity in the cost calculations and economic inputs in order to simplify later cost calculations.

Several suggestions centered on the GDsalt GUI. Multiple groups suggested integrating the *beneficial-use* selection into the initial user inputs, rather than being a pop-up selection that the user must select after the program is already running. One group suggested the addition of an output tab to the GUI that would allow the user to copy the run results to another workbook. This option would be very helpful, especially if the output option included the initial user inputs, and would allow for a more comprehensive comparison of results. Increasing the size of the user preferences window would decrease or eliminate the need to scroll through the lists, making the program easier to use. For the geothermal input, it would be beneficial to add an option for steam. Finally, there were many suggestions on the inclusion/exclusion of treatment processes. One team suggested that the inclusion and exclusion lists should be merged, while also adding checkboxes, with “select all” checkboxes for the subsections of pretreatment, desalination, and post-treatment.

Two teams encountered errors while using the program. The teams stated that the program would not allow them to include a specific desalination technique in the selection process, and they were forced to exclude every process except the one desired desalination technique. The second team was given an error while GDsalt was running saying that it had to be re-run. When the team clicked “okay,” the program began a non-stop loop—encountering the error, but not allowing the user to escape back to the home screen to fix the error. In this case, the team had to restart the program. Therefore, an option to cancel a program run was recommended.

Finally, one team struggled with understanding why there was no difference in some process trains and requested more analysis detail on removal rates of contaminants in order to understand GDsalt’s selections. They also asked for the option to rank selections based on the individual user input scores rather than the overall process score. Such information is beyond what could be provided within GDsalt, but may be appropriate for a user manual.

The engineers at NREL and CSM’s Advanced Water Technology Center reviewed the results of this testing, as well as the suggestions for improvement for the GDsalt program. The revised form of GDsalt is available for users, in addition to an updated user manual for the tool. The spreadsheet tool and manual can be obtained at the AQWATEC website at http://aqwatec.mines.edu/research/GT_Desal/

4 Desalination Technologies

4.1 Thermal Technology Options and Effect of Plant Capacity

Desalination is a multibillion dollar, worldwide industry. As such, there have been numerous assessments of desalination technologies and costs. Representative costs for desalinated water is presented in Figure 5 [7]. Multistage flash (MSF), multi-effect distillation (MED), and reverse osmosis (RO) are the top three desalination technologies in terms of worldwide installed capacity [7]. RO is an all-electric technology, whereas MSF and MED are primarily thermal, with some electric demand for pumping and controls. RO is the leading desalination technology worldwide and is typically the lowest-cost option for seawater desalination.

For geothermal desalination designs, one could employ the geothermal source for electric power production and couple that power source with an RO system. However, electricity generation with a low-temperature geothermal resource is very inefficient, so direct use of the geothermal heat is preferred. Examining the thermal desalination processes in Figure 5, one notes that the dominant cost categories are the capital equipment and the cost for thermal energy. Thus, the ideal technology for geothermal desalination would be a thermal technology with a low capital cost, especially at small scale. Thermal energy consumption is a lesser concern, assuming one can tap into a low-cost geothermal heat source.

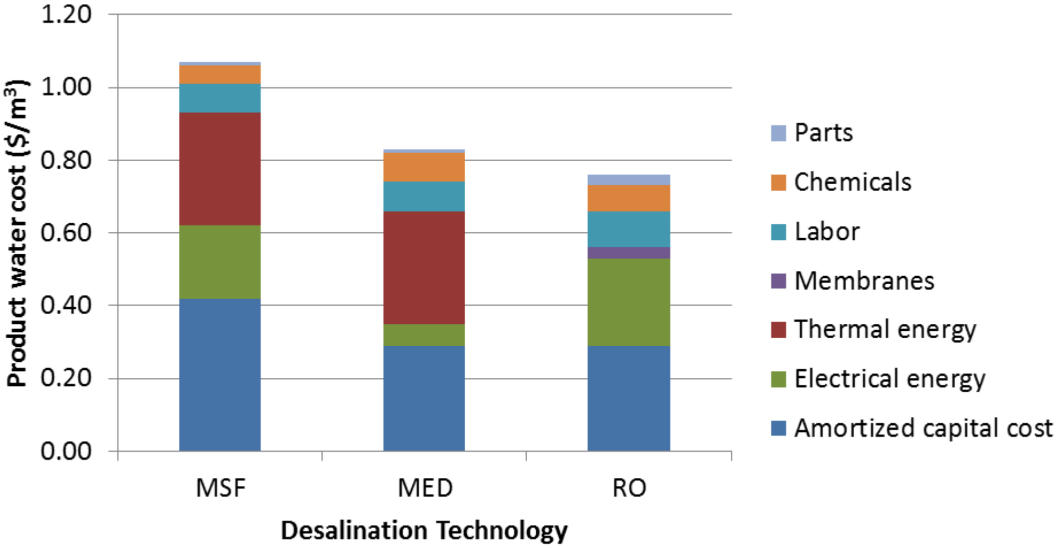


Figure 5. Distribution of cost by category for common desalination technologies [7]. Values are based on a large seawater desalination plant.

As with many technologies, the cost of the product varies with plant size, although the different technologies exhibit different sensitivity to scale. Kesieme and coworkers [8] highlight the variation in product-water cost with plant size, as shown in Figure 6. The greatest cost reductions occur when one moves from small plant capacities (less than 1,000 m^3/day) to a few thousand cubic meters per day. The cost of membrane-based systems, such as RO and membrane distillation (MD), is less sensitive to plant capacity due to the modular nature of these technologies.

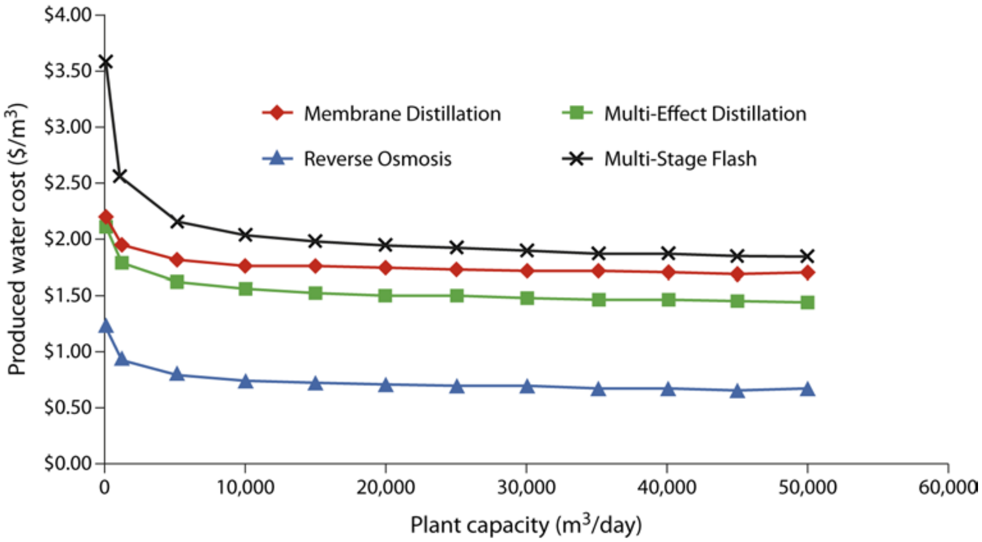


Figure 6. Modular RO and MD desalination technologies are less sensitive to economies of scale than MSF and MED [8]. This makes RO and MD technologies a better match for small plant sizes.

Geothermal desalination systems are expected to be relatively small-capacity units

Assuming a 40ºC temperature differential and a geothermal well flowing at 4 m^3/min (1,080 gpm), the available geothermal energy is about 11.2 MW_{th} or 270 MWh_{th} per day. Thermal desalination processes are governed by the latent heat of vaporization of water, which is about 2,270 kJ/kg (630 kWh/m^3); thus, in the absence of energy recovery, the maximum water production from such a geothermal source is about 426 m^3/day:

$$Q_{geo} = \dot{m}_{brine} Cp\Delta T = (4000\ kg/min)*(4.2\ kJ/kg\text{-}K)*(40\ K) = 672{,}000\ kJ/min = 11{,}200\ kW_{th}$$

$$\dot{m}_{water} = Q_{geo}/\Delta H_{vap} = (672{,}000\ kJ/min)\ /\ (2270\ kJ/kg) = 296\ kg/min = 426\ m^3/day$$

A common figure of merit, the gained-output ratio (GOR), is defined as the mass of water produced per mass of steam fed to the process, where the mass of steam is a surrogate for the latent heat of steam. Accordingly, in the calculations above, an energy demand of 630 kWh_{th}/m^3 represents $GOR = 1$. Heat recovery is applied in thermal desalination systems to improve thermal efficiency, albeit at greater hardware cost. Multiple stages or *effects* are added to recover the heat of vaporization by preheating the next effect. Optimizing the number of effects is a tradeoff between initial capital cost and complexity versus energy use and operating cost. Typical GOR values for commercial MED systems range from 6–10 [9]. Even at $GOR = 10$, the daily production in our example case is only about 4,000 m^3/day. Clearly, desalination systems designed to take advantage of low-grade geothermal heat must be suitable for implementation at the relatively small scale of hundreds to a few thousand cubic meters per day.

Best small-capacity thermal desalination choice

The assumption that geothermal desalination facilities will be of modest capacity strengthens the rationale for selecting a modular technology such as MD for integration with the geothermal resource. Figure 7 compares the cost categories as a function of system capacity for two thermal desalination technologies—MED and MD. The advantage of MED shrinks as system capacity decreases. The MD technology cost is less sensitive to system capacity, but is more sensitive to thermal-energy cost than the MED technology. This suggests that MD will be favored as one moves toward small-capacity units and can take advantage of low-cost thermal-energy sources. In fact, Kesieme and coworkers highlighted this in their recent analysis. Figure 8 illustrates how the MD system becomes the lowest-cost technology—versus MED or RO—at low thermal-energy costs. Furthermore, the advantage of MD is greatest at the lowest plant capacities.

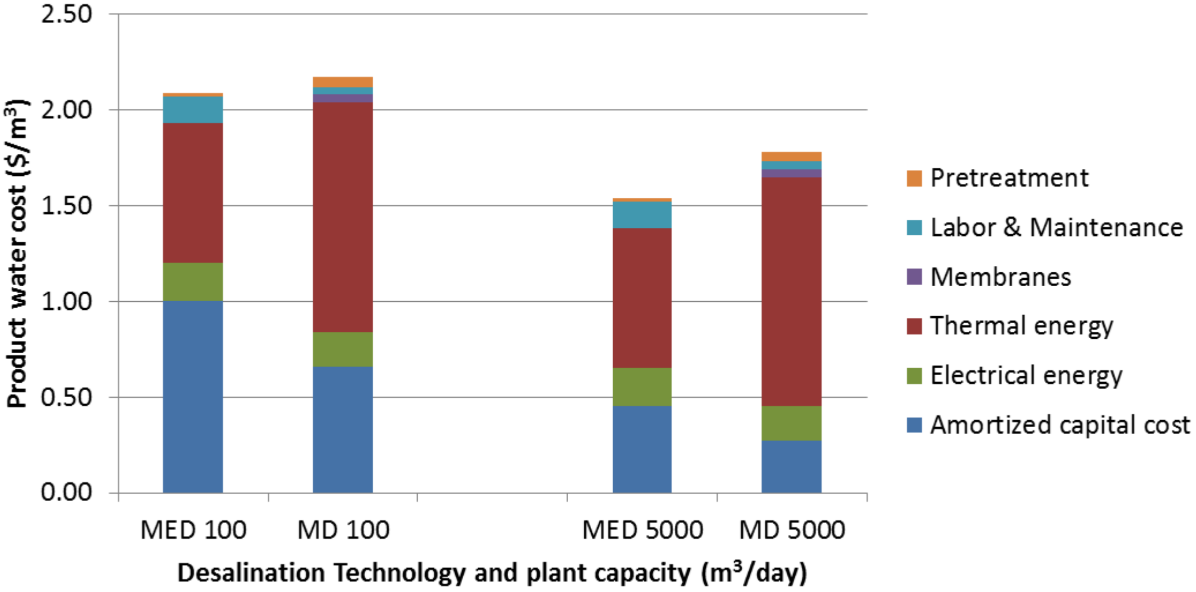


Figure 7. Comparison of two thermal desalination technologies: MED and MD. At either scale, MD exhibits a lower capital cost but greater thermal-energy consumption. Data from [8].

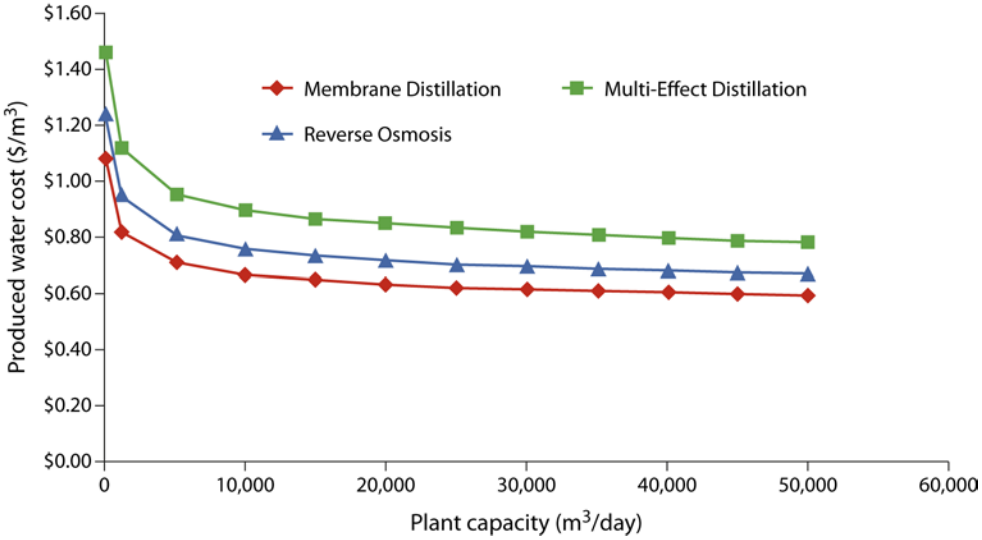


Figure 8. The combination of modularity and reliance on thermal energy means that MD systems can be the lowest-cost desalination option in small systems if low-cost thermal energy is available. This chart repeats the analysis shown in Figure 6, assuming a tenfold decrease in thermal-energy costs [8].

Walton et al. [10] also developed a cost estimate for MD as a function of thermal energy, assuming that the capital cost of the facility is the same as for seawater RO (\$0.375/m^3); they also compared it to RO, assuming the energy cost of RO accounted for 50% of the total water cost. Walton et al. concluded that MD is competitive relative to RO when low-cost heat energy is available and when the water chemistry of the source water is too difficult for treatment with RO.

4.2 Membrane Distillation: A Good Match for Geothermal

Membrane distillation was originally proposed in the 1960s, but has only recently been the subject of commercial interest because the technology to produce thermally stable membranes has improved. MD offers several potential advantages, including that it:

- Produces superior product water-quality compared to RO. High-purity product water is a general characteristic of thermal desalination technologies. Although this can be valuable in some applications (e.g., producing boiler feedwater), some mineral content needs to be added for potable use;
- Can treat higher-salinity brines than RO;
- Uses low-grade heat for its primary energy input (<100ºC);
- Accommodates sensible (e.g., hot water) heat input;
- Operates at near-ambient pressure;
- Uses lower-cost membranes due to pressure and temperature conditions that allow use of inexpensive plastics (e.g., PVDF, polypropylene) as construction material and a pore size that is orders-of-magnitude larger than required for RO membranes;
- Provides a modular design that is amenable to small-scale facilities; and
- Can tolerate variable operating conditions, including stop/start cycles.

It should be noted that although MD filters are simpler than RO membranes, production volume of MD membranes is, at present, much lower than RO membranes, thus negating the potential cost advantage at this time.

The basic components of an MD system are depicted in Figure 9. The MD process uses hydrophobic, microporous membranes and the driving force is the partial vapor-pressure difference across the membrane. There are various implementations of the basic MD technology to improve efficiency—for example, air-gap MD and sweep-gas MD—but they share the attributes listed above. Camacho [11] states that MD has thermal-energy requirements ranging from 120 to 1,700 kWh/m^3 (GOR = 0.4 to 5.2) depending on conditions and design. Data given from two MD developers, Aquastill and Memsys, list thermal-energy demands of 56 to 350 kWh$_{th}$/m^3 (GOR = 1.8 to 11) [11].

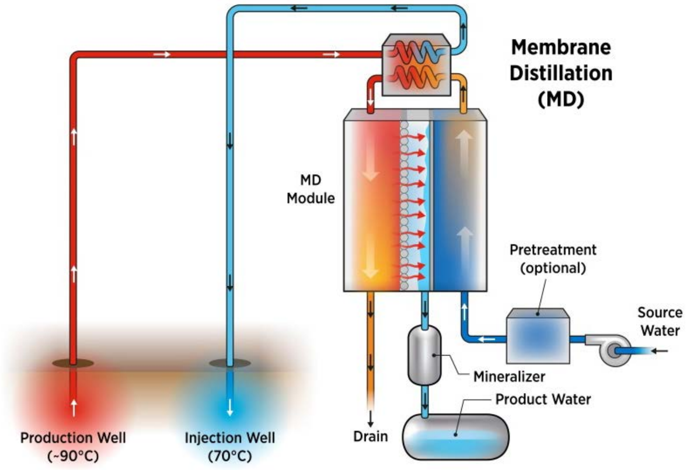


Figure 9. Basic MD system with a hot source water. Water vapor passes through the membrane from the hot-brine side to the cool-permeate side.

The simplest form of MD is direct-contact membrane distillation (DCMD), as illustrated in Figure 10a. DCMD is favored in many trials due to its simplicity; however, thermal conduction across the membrane makes this the least-efficient form. In air-gap MD (AGMD, Figure 10b), the air gap is usually the controlling factor for the mass and heat transfer because of its greater thermal and mass-transfer resistances. In comparison with the thickness (40–250 µm) and conductivity of the membrane, the air gap is much thicker (2,000–10,000 µm) and has lower thermal conductivity [11]. Therefore, more thermal energy in AGMD will be used for water evaporation than in DCMD. Additionally, if a low-temperature feed is used as the cooling stream in this configuration, the latent heat can be recovered through the condensation of the vapor on the cooling plate. However, AGMD typically has a low flux, due to the low temperature difference across the membrane, and therefore, larger surface areas are required.

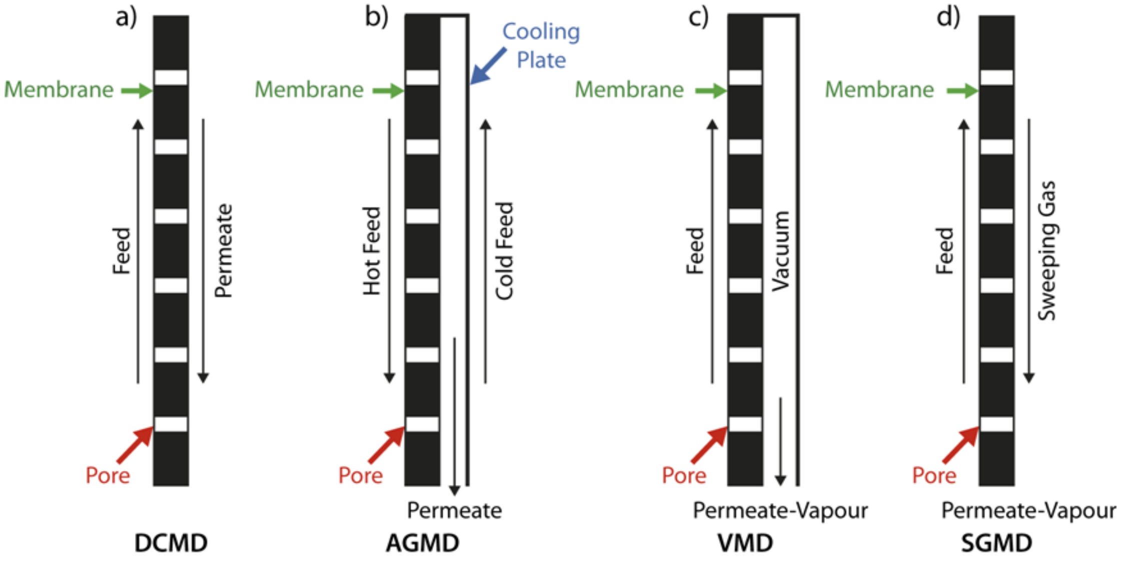


Figure 10. Basic types of membrane distillation: (a) direct-contact MD, (b) air-gap MD, (c) vacuum MD, and (d) sweep-gas MD [11].

Vacuum MD and sweep-gas MD endeavor to increase thermal efficiency and/or flux, but require more hardware, which somewhat negates MD's advantage of simplicity. AGMD has been deployed by one developer (Dutch developer Aquastill), and vacuum MD is being promoted by Aquastill and the German company Memsys GmbH, which recently partnered with GE to explore the treatment of produced water from the oil and gas industry (http://www.memsys.eu/). The Memsys/GE partnership is targeting MD treatment of water that is challenging for other desalination technologies (see Figure 11).

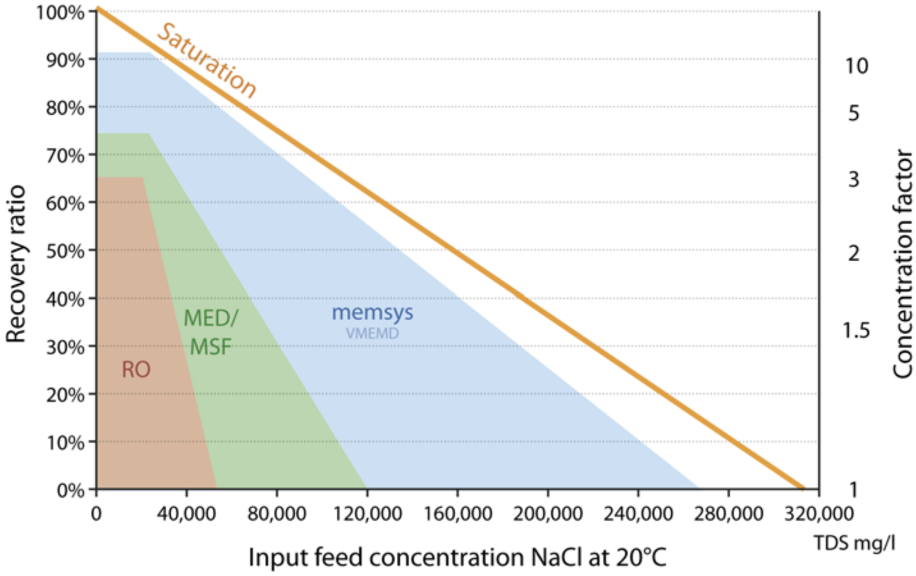


Figure 11. Plot of recovery ratio vs. TDS, showing regions of applicability of different desalination technologies [12]. MD systems can achieve recovery fractions and handle high-TDS waters that RO cannot. The arrows show hypothetical treatment strategies.

4.3 Membrane Distillation: Costs and Opportunities

Camacho's [11] review of the literature indicates than MD can produce high-purity water from poor-quality source water at a cost in the range of \$1.2/m^3, which could be lowered to less than \$0.5/m^3 if low-cost heat is available. Realizing Camacho's lower bound will require taking advantage of the potential capital-cost savings of the emerging MD technology, as well as providing low-cost thermal energy—for example, from low-enthalpy geothermal sources such as unused wells or reinjection brine.

Al-Obaidani et al. [13] performed an MD cost analysis based on a combined membrane/element cost of \$90/m^2. There are no dedicated MD membranes on the market, but classical microfiltration membranes that are used in commercial MD units exhibit good fluxes and selectivity. Since 2008, the market for ultra/microfiltration membranes has grown and costs have decreased. The most recent in-house economic models of CSM use a microfiltration membrane and element cost of \$14/m^2 and \$24/m^2, respectively. The combined cost of \$38/m^2 is less than half the cost assumed by Al-Obaidani in 2008. Given that Al-Obaidani reported that membrane/element costs account for about 50% of the total cost, this represents an approximate 25% drop in capital cost for the MD system over the past seven years.

Kesieme et al. [8] identified scenarios where MD could be competitive with state-of-the-art desalination technologies, such as RO or MED. Compared to MED, MD is predicted to have lower capital cost, but higher thermal-energy requirements (see Figure 12). The cost divisions indicate that low-cost thermal energy, for example, from a geothermal source, will have a more pronounced impact on MD costs than on the cost of MED.

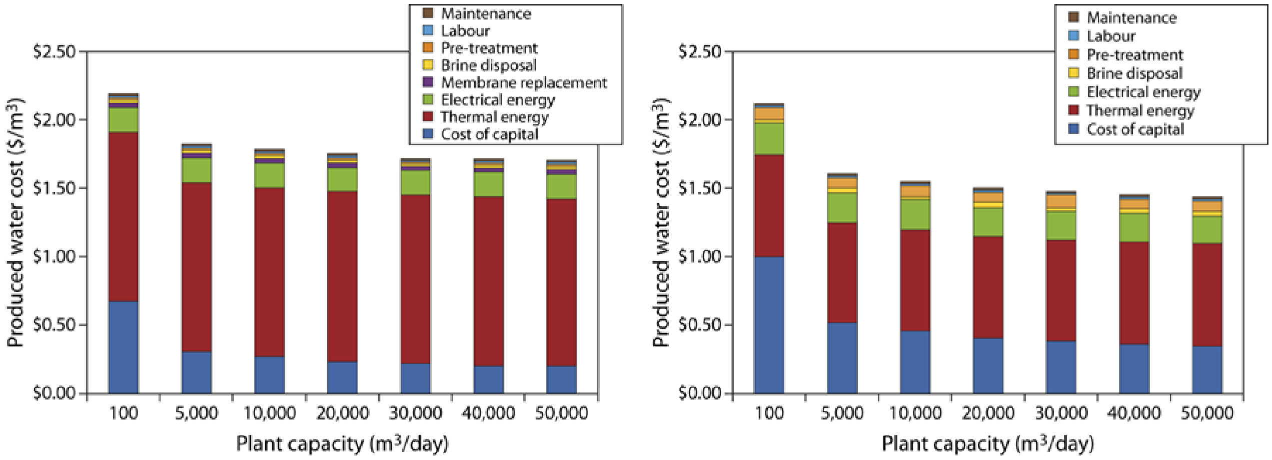


Figure 12. Water cost by cost category for MD (left) and MED (right) systems [8]. For MD, overall cost is dominated by the cost of thermal energy.

Furthermore, from Kesieme's calculations, one can determine the cost of thermal energy that brings MD in line with a target cost of about $1/m^3$. Kesieme assumed the cost of thermal energy from steam generated in a natural gas boiler was $0.0124/kWh$_{th}$ ($3.6/MMBtu). Examining the 5,000 m^3/day bar in Figure 12, we note that if thermal-energy costs are reduced by 66%, the estimated MD cost for product water drops to about $1/$m^3$. (The value drops to about $1.4/$m^3$ at the 100 m^3/day capacity.) This cost, $0.0041/kWh$_{th}$ or ~$1.2/MMBtu, is compared to the cost of heat generated from potential geothermal sources in Section 5.2.

In Kesieme's analysis (Figure 12), MED is lower cost than MD at all except the smallest plant sizes. However, if low-cost thermal energy is available, the cost advantage shifts toward MD. As with RO, MD retains an advantage over MED in that it is able to operate over a wider range of conditions. MD can operate at slightly higher concentrations versus MED because the temperature drops throughout the MD module, solubilizing common scalants such as $CaCO_3$. More importantly, MD can operate at much lower temperatures than MED, enabling the use of much lower-value and more-abundant heat sources. The minimum feed temperature for MED is 70ºC, whereas there is technically no limit to the hot-side temperature of MD as long as the distillate temperature is lower [14].

Moreover, based on the assessment by NREL/CSM, Kesieme's assumed electrical consumption of 2 kWh/m^3 for MD is conservative, which might further lower cost. For comparison, CSM has ordered two 27-m^2 MD modules from Aquastill in the Netherlands with a claimed electrical consumption of 0.313 kWh/m^3. Recently, new MD configurations have been suggested with order-of-magnitude lower electrical consumption due to much higher water recoveries [15]. CSM is working closely with Aquastill to test the performance and scalability of these new modules.

4.4 Challenges for Membrane Distillation

In MD processes, heat and mass transfer are coupled, and it is desired to minimize the former and maximize the latter. Water evaporates and is transported across the hydrophobic membrane, while heat is simultaneously conducted through the membrane from the feed stream to the product (distillate) stream. The driving force for mass transfer is the partial vapor-pressure difference across the membrane—that is, between T_1 and T_2 in Figure 13. Reducing the boundary layers on either side of the membrane is an important path to increasing mass transport. If this is accomplished (e.g., through the use of flow-turbulence enhancers and/or VMD or SGMD), the mass transport will be governed by diffusion through the membrane.

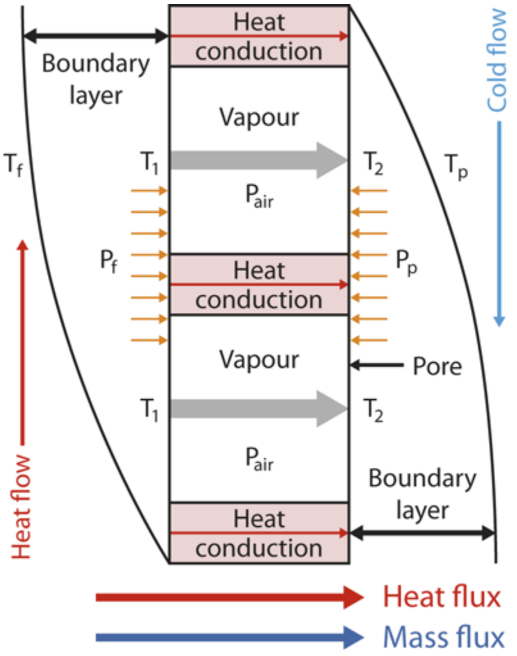


Figure 13. Heat and mass transfer across a membrane [11].

The most common materials used for MD membranes are polytetrafluoroethylene (PTFE), polypropylene (PP), and polyvinylidenefluoride (PVDF). The porosity of the membranes ranges from 0.60 to 0.95, the pore size ranges from 0.2 to 0.5 µm, and the thickness ranges from 0.04 to 0.25 mm [11]. PTFE has the highest hydrophobicity, but also the highest thermal conductivity and cost. Membranes can be provided as sheets, spiral-wound modules, or hollow-core fibers. Good MD membranes must balance several factors:

- Thickness. Thinner membranes increase membrane permeability (which is good; better mass flux) and decrease thermal resistance (which is bad; lower thermal efficiency). Membranes must also be thick enough to provide mechanical strength.
- Reasonably large pore size and narrow pore-size distribution, limited by the minimum liquid entry pressure (LEP) of the membrane. In MD, the hydrostatic pressure must be lower than LEP to avoid membrane wetting.
- Low surface energy, equivalent to high hydrophobicity. Materials with higher hydrophobicity can be made into membranes with larger pore sizes, or membranes made

from more hydrophobic material will be applicable under higher pressures for a given pore size.

- Low thermal conductivity to minimize heat transfer and reduce vapor flux due to reduced interface temperature difference.
- High porosity. High porosity decreases thermal transfer and increases mass transfer, so both the heat efficiency and mass flux are increased. However, high-porosity membranes have low mechanical strength and tend to crack or compress under mild pressure, which results in the loss of membrane performance.

Membrane fouling is a major obstacle in the application of all membrane technologies, because it causes flux to decline. The foulant (e.g., bio-film, precipitations of organic and inorganic matter) can reduce the permeability of a membrane by clogging the membrane surface and/or pores. Dow et al. [16] showed that lower feed temperatures typical of MD can substantially reduce the influence of fouling in direct-contact MD. Scale formation is traditionally managed in water systems by use of anti-scalants.

Because the hydrophobic MD membrane is the barrier between the feed and permeate, membrane wetting will reduce the rejection of the non-volatiles and degrade product-water quality. Membrane wetting can occur under the following conditions [11]:

- The hydraulic pressure applied on the surface of the membrane is too high,
- A foulant depositing on the membrane surface can effectively reduce the hydrophobicity of the membrane,
- Organic materials or surfactants in the source water can adsorb to the membrane and reduce the hydrophobicity of the membrane, or
- Organic materials or surfactants in the source water can lower the surface tension of feed solution.

MD is driven by partial vapor-pressure difference, which varies exponentially with the stream temperature; thus, the flux is affected greatly by the feed temperature. Furthermore, because the heat loss through thermal conduction varies only linearly with temperature difference across the membrane, the proportion of energy used for evaporation will increase as the feed temperature increases. Although MD systems can operate at lower temperatures than other thermal desalination processes, the benefits of greater flux generally influences one to operate at the highest temperature that the membrane and heat source allow.

5 Low-Temperature Geothermal Resources

5.1 Prevalence

As reported by the U.S. Geological Survey, most of the identified low-temperature geothermal systems are hydrothermal convection systems, which can be subdivided into isolated systems and delineated-area systems [17]. *Isolated* systems are hydrothermal reservoirs with surface evidences and thermal springs, or a well that produces thermal water. They have geologic control and commonly occur along normal faults or folded and thrusted rocks. *Delineated-area* systems are characterized by the upflow of thermal water along faults and its subsequent lateral movement into aquifers at relatively shallow depths. There may not be an associated discharge of thermal springs at the surface, and the shallow thermal aquifer may be underlain by a hotter reservoir at greater depths. The beneficial heat available from the low-temperature resource can be calculated as a fixed fraction of the wellhead thermal energy using the empirical equation given below [17]:

$$q_{ben} = 0.6\rho C \left(\frac{ka}{a_w}\right) \cdot Q \cdot P \cdot (T_r - 25)$$

where:

q_{ben}	Beneficial heat (MW_{th})
Q	Volumetric flow
ρC	Volumetric specific heat (J/cm^3-K)
k	Transmissivity constant (values between 0 and 1)
a	Reservoir area (km^2)
a_w	Optimum reservoir area per well (km^2)
P	Duration of production period
$(T_r - 25°C)$	Usable temperature dropdown (°C)
(ka/a_w)	Mean number of wells each reservoir can support according to the reservoir flow

The units for reporting beneficial heat are megawatts thermal (MW_{th}) for 30 years, and the values obtained represent energy that might actually be used in applications at the surface. Mean resource energy for each identified thermal reservoir is calculated either by assuming a 25% recovery factor for those reservoirs with a standard volume of 1 km^3, or by estimating the number of production wells that a reservoir with a larger-than-standard volume can support for 30 years with a cumulative drawdown of 152 m [17]. Table 5 lists the total estimated resource capacity for identified isolated systems and delineated geothermal systems having mean reservoir temperature between 50°C and 90°C. It should be noted that the USGS is currently updating the 1982 assessment of low-temperature geothermal resources [18].

Table 5. Distribution of geothermal beneficial heat and mean resource energy by state for hydrothermal convectional systems having mean reservoir temperature between 50°C and 90°C (Original data source is [17])

	Hydrothermal-Convectional*						
	Isolated Systems			Delineated Systems			
States	Beneficial Geothermal Heat (MW_{th})	Mean Resource Energy (10^{18} J)	Mean Resource Energy (10^{12} Btu)	Beneficial Geothermal Heat (MW_{th})	Mean Resource Energy (10^{18} J)	Mean Resource Energy (10^{12} Btu)	Total (MW_{th})
Washington	75	0.158	150	0	0.000	0	75
Texas	115	0.235	223	0	0.000	0	115
Wyoming	129	0.475	450	0	0.000	0	129
New Mexico	288	0.570	540	29	0.055	52	317
Colorado	308	0.975	924	67	0.080	76	375
Alaska	399	0.784	743	0	0.000	0	399
Montana	428	0.838	794	0	0.000	0	428
Utah	214	0.435	412	263	0.860	815	477
Oregon	602	1.191	1,129	487	1.130	1,071	1,089
California	937	1.847	1,751	271	1.547	1,466	1,208
Arizona	426	0.846	802	829	1.767	1,675	1,255
Nevada	863	1.683	1,595	1,055	2.231	2,115	1,918
Idaho	1,361	2.676	2,536	728	1.425	1,351	2,089
TOTAL	**6,145**	**12.713**	**12,050**	**3,729**	**9.095**	**8,620**	**9,874**

Figure 14 illustrates the low-temperature geothermal beneficial potential overlaid with the corresponding potential desalination potential, assuming GOR = 4. Idaho, Nevada, Arizona, California and Utah are the top five states. The predicted desalination potential in California is approximately 184,000 m^3/day (50 MGD), which is approximately equal to the capacity of the new Carlsbad Desalination Plant near San Diego [19].

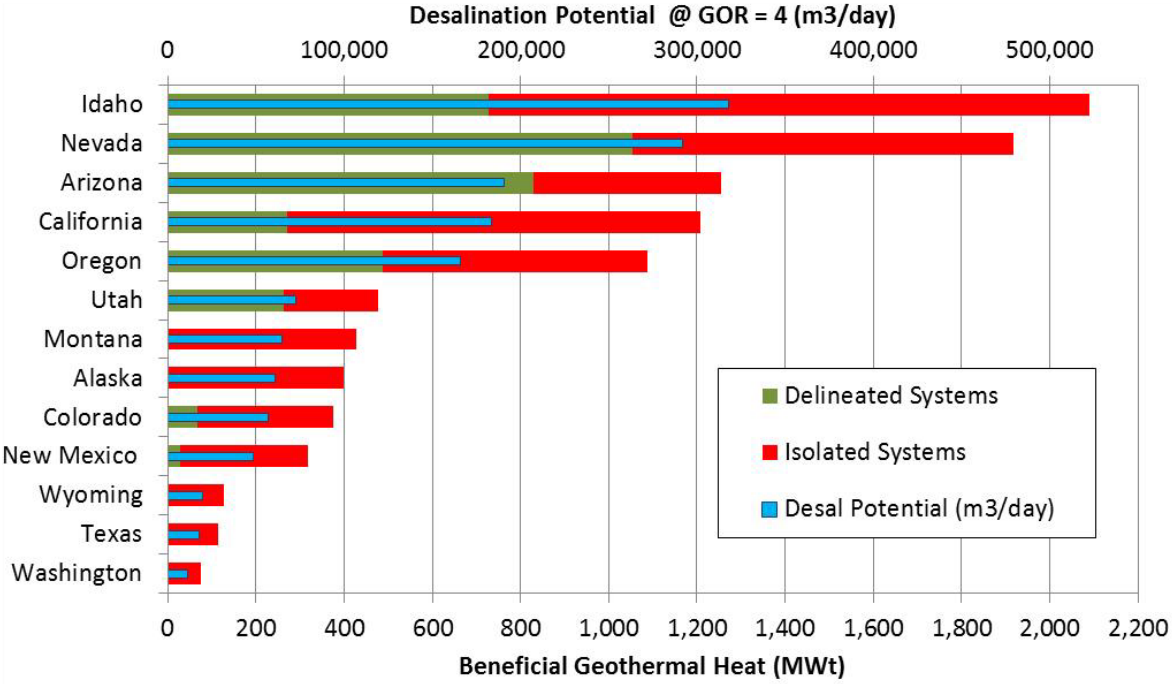


Figure 14. Estimated beneficial geothermal heat and desalination potential by states originating from hydrothermal convectional systems [17]. Desalination estimates assume GOR = 4.

Based on the Oregon Institute of Technology Geo-Heat Center and other geothermal databases, there are more than 900 geothermal wells having temperatures between 50°C and 90°C in the United States (Figure 15). Most of these wells are already used for direct-heat applications. In addition to these wells, many more inactive and unproductive oil and gas wells can be used for thermal-energy production. An example of these wells is the Gulf No.1 well in Presidio, TX, which is 2073 m deep and has a temperature of 82°C and a flow rate of 138 L/s [20].

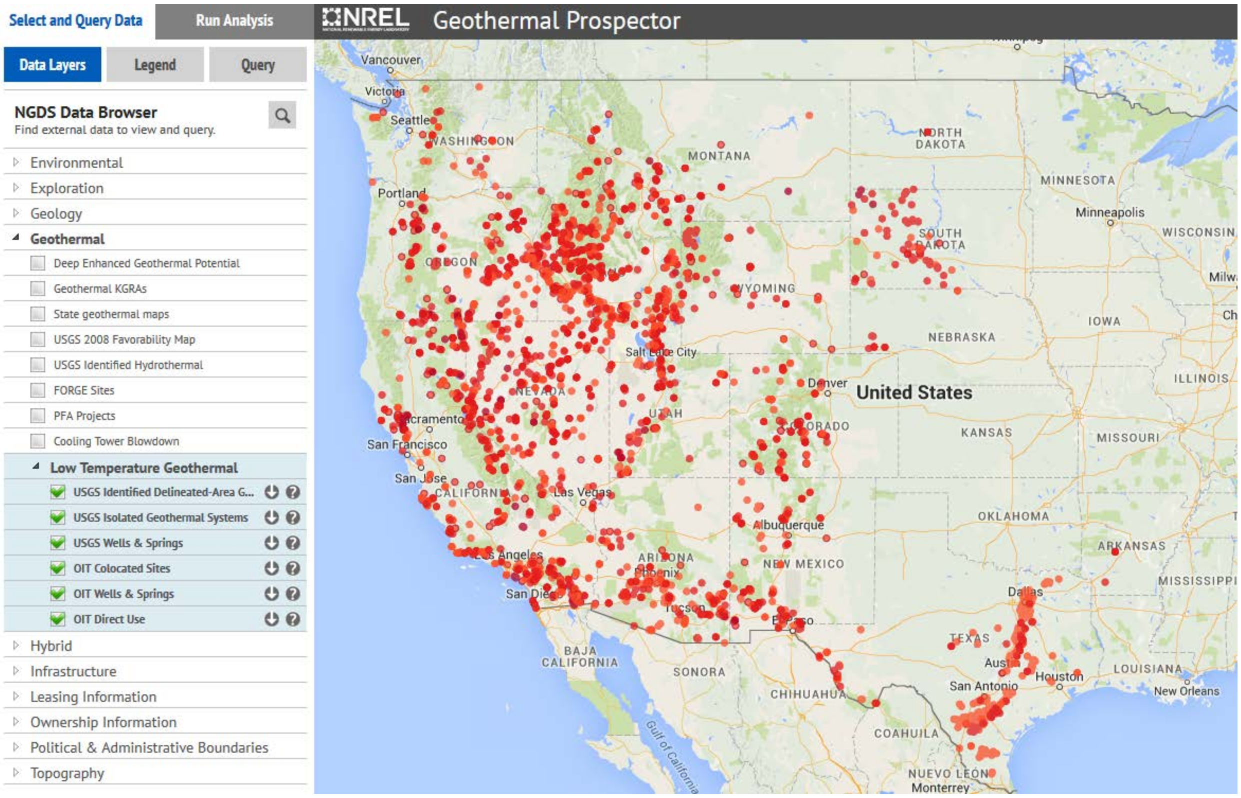


Figure 15. Distribution of low-temperature (between 50°C and 90°C) geothermal wells suitable for MD technology.

5.2 Thermal-Energy Cost

The successful integration of MD with geothermal heat depends on that heat being available at very low cost. In this section, we estimate the cost of geothermal heat and compare it to other energy sources. Table 6 and Table 7 outline the estimated levelized cost of heat (LCOH) for different geothermal source cases. The LCOH is defined as a convenient metric for estimating lifetime cost for geothermal direct-use applications. LCOH is defined analogously to LCOE, which conventionally refers to electric energy. In its simplest form, LCOH is defined as:

$$LCOH = \frac{(Total\ installed\ project\ cost) * (FCR) + (Annual\ O\&M)}{Annual\ thermal\ generation} \quad (1)$$

where FCR is the fixed charge rate and depends on a range of financial parameters that can have a significant influence on LCOH. The latest release of NREL's System Advisor Model (SAM, version 2015-06-30) includes a procedure for estimating and using the FCR method, which is used in this study. More information on the approach is summarized in Appendix E.

Table 6. Summary of LCOH estimates for different production scenarios from new geothermal wells*

	Units	Case-1: New Geothermal Well			
Geothermal Field Characteristics		**Scenario 1.1**	**Scenario 1.2**	**Scenario 1.3**	**Scenario 1.4**
Production Temperature	°C	100	100	100	90
Re-Injection Temperature	°C	70	70	70	60
Temperature Gradient	°C/100m	5	6	7	5
Drilling Depth	m	1500	1250	1071	1300
Flow Rate/well	L/s	89	89	89	87
Total Flow Rate	L/s	89	89	89	174
Thermal Energy Capacity	MWt	11.15	11.15	11.15	21.80
Capacity Factor	%	90%	90%	90%	90%
Annual Operational Hours	h	7884	7884	7884	7884
Annual Production	kWht/yr	87,906,600	87,906,600	87,906,600	171,871,200
# Production Wells		1	1	1	2
# Re-Injection Wells		1	1	1	1
CAPEX					
Development Cost	$	1,000,000	1,000,000	1,000,000	1,000,000
Drilling Cost (production or Re-injection)	$/well	2,250,003	1,562,502	1,147,961	1,690,002
Total Drilling Cost (1 prod. & 1 Re-inj.)	$	4,500,006	3,125,005	2,295,922	5,070,007
Well Head equipment Cost (total)	$	300,000	300,000	300,000	500,000
Pump Cost (ESP)	$	500,000	500,000	500,000	1,000,000
Piping Cost*	$	300,000	300,000	300,000	600,000
Total	**$**	**6,900,006**	**5,525,005**	**4,695,922**	**8,670,007**
OPEX					
Production Well Pumping (Electricity)*	$/yr	211,883	211,883	211,883	423,765
Inhibitor Cost	$/yr	50,000	50,000	50,000	100,000
Labor Cost	$/yr	150,000	150,000	150,000	150,000
Re-Injection Cost	$/yr	150,000	150,000	150,000	250,000
Total	**$/yr**	**561,883**	**561,883**	**561,883**	**878,495**
Financial Assumptions					
Weighted average cost of capital	%	6.2%	6.2%	6.2%	6.2%
Project life	years	20	20	20	20
Calculated fixed charge rate	-	0.101	0.101	0.101	0.101
Levelized Cost of Heat (LCOH)	**$/kWht**	**0.0143**	**0.0127**	**0.0118**	**0.0102**
Levelized Cost of Heat (LCOH)	**$/MMBtu**	**4.2**	**3.7**	**3.5**	**3.0**

* Major assumptions: (i) 1000-m spacing between production and re-injection well, (ii) unit cost of insulated pipe $300/m, (iii) 250-kW average electricity consumption for a submersible pump to produce flow rate of 88 L/s, and (iv) 2014 commercial U.S. average electricity price of 10.7 ¢/kWh.

Table 7. Summary of LCOH estimates for different production scenarios from existing geothermal wells and existing power plant cases*

	Units	Case-2: Existing Geothermal Well		Case-3: Existing Geothermal Power Plant	
Geothermal Field Characteristics		**Scenario 2.1**	**Scenario 2.2**	**Scenario 3.1**	**Scenario 3.2**
Production Temperature	°C	100	100	70	80
Re-Injection Temperature	°C	70	60	50	50
Temperature Gradient	°C/100m	NA	NA	NA	NA
Drilling Depth	m	NA	NA	NA	NA
Flow Rate/well	L/s	89	80	NA	NA
Total Flow Rate	L/s	89	160	80	160
Thermal Energy Capacity	MWt	11.15	26.70	7.4	13.4
Capacity Factor	%	90%	90%	90%	90%
Annual Operational Hours	h	7884	7884	7884	7884
Annual Production	kWht/yr	87,906,600	210,502,800	58,341,600	105,645,600
# Production Wells		1	2	NA	NA
# Re-Injection Wells		1	1	NA	NA
CAPEX					
Development Cost	$	0	0	0	0
Drilling Cost (production or Re-injection)	$/well	0	0	0	0
Total Drilling Cost (1 prod. & 1 Re-inj.)	$	0	0	0	0
Well Head equipment Cost (total)	$	300,000	500,000	0	0
Pump Cost (ESP)	$	500,000	1,000,000	100,000	100,000
Piping Cost*	$	300,000	600,000	60,000	60,000
Total	**$**	**1,400,000**	**2,600,000**	**160,000**	**160,000**
OPEX					
Production Well Pumping (Electricity)*	$/yr	211,883	423,765	0	0
Inhibitor Cost	$/yr	50,000	100,000	100,000	150,000
Labor Cost	$/yr	150,000	150,000	30,000	30,000
Re-Injection Cost	$/yr	150,000	250,000	75,000	125,000
Total	**$/yr**	**561,883**	**878,495**	**205,000**	**305,000**
Financial Assumptions					
Weighted average cost of capital	%	6.2%	6.2%	6.2%	6.2%
Project life	years	20	20	20	20
Calculated fixed charge rate	-	0.101	0.101	0.101	0.101
Levelized Cost of Heat (LCOH)	**$/kWht**	**0.0080**	**0.0054**	**0.0038**	**0.0030**
Levelized Cost of Heat (LCOH)	**$/MMBtu**	**2.3**	**1.6**	**1.1**	**0.9**

* Major assumptions: (i) 1000-m spacing between production and re-injection well, (ii) unit cost of insulated pipe $300/m, (iii) 250-kW average electricity consumption for a submersible pump to produce flow rate of 88 L/s, and (iv) 2014 commercial U.S. average electricity price of 10.7 ¢/kWh.

The cases in Table 6 and Table 7 cover three primary scenarios: (Case 1) new production and injection wells must be drilled for the geothermal resource, (Case 2) existing, but used, production and injection wells are used that must be completed and maintained, and (Case 3) geothermal heat is siphoned off an existing geothermal power plant prior to reinjection. Case 1 is further divided into different resource qualities similar to other work [21]. LCOH is estimated for the different cases using a set of financial assumptions taken from SAM's default values. The resulting LCOH ranges from \$0.003/kWh$_{th}$ to \$0.014/kWh$_{th}$ (\$0.9 to \$4.2/MMBtu).

A convenient comparison for thermal-energy cost in the United States is a natural gas boiler. The estimated cost of thermal energy from a natural gas boiler compared to geothermal heat is shown in Figure 16. For the assumptions here, about 80% to 90% of the total levelized cost for the gas heat is due to fuel. In 2014, the average price for industrial natural gas in the United States was about \$5.5/MMBtu [22]. Figure 16 indicates that geothermal heat is clearly less expensive than heat from a gas boiler at those 2014 average gas prices. Furthermore, if existing, underutilized wells can be purposed for desalination, the cost of geothermal energy is about one-third that of heat from a gas boiler at current gas prices. The advantage is even greater if one considers the California market, where the average industrial gas price in 2014 was \$7.7/MMBtu [22].

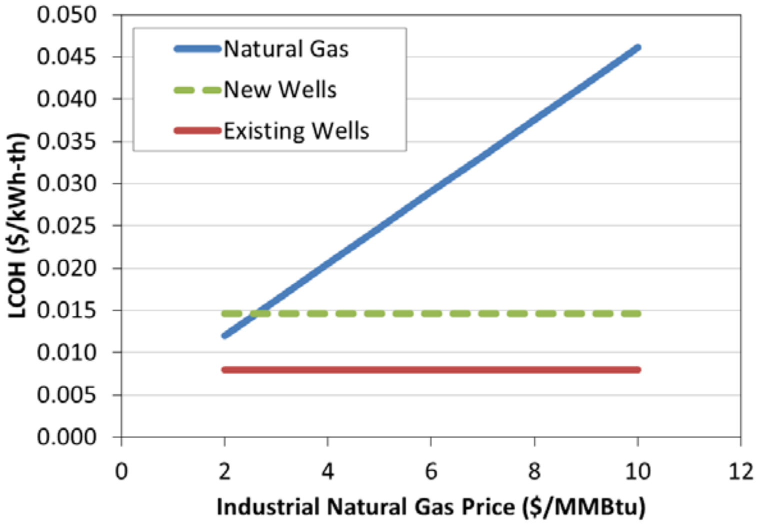


Figure 16. LCOH for natural gas boiler and geothermal sources as a function of industrial gas price. The calculation assumes an 80% boiler efficiency, 90% availability, and \$270/kW$_{th}$ installed capital cost. Geothermal assumptions are listed in Table 6 and Table 7.

The cost of thermal energy assumed in prior desalination cost studies is an important consideration. The work by Kesieme and co-workers [8], discussed previously, assumed a steam cost of \$0.0124/kWh$_{th}$. This is a relatively low value compared to the estimated cost of heat from natural gas in Figure 16 and corresponds to a gas price of about \$2/MMBtu. Based on Kesieme's work, at the scale of 5,000 m^3/day, a thermal-energy cost of about \$0.004/kWh$_{th}$ is necessary for the MD technology to hit a product-water cost target of \$1/m^3. The thermal-energy cost to achieve \$1.5/m^3 is about \$0.009/kWh$_{th}$. Product-water costs are about \$0.4/m^3 higher at the smaller scale of 100 m^3/day.

Basically, thermal energy can be obtained from geothermal resource in three different cases: 1) drilling new wells in a proven resource area, 2) using existing geothermal wells that are actively used by the operators and not suitable for electricity generation, and 3) using outlet brine from existing geothermal power plants. Cost of thermal energy from geothermal resources is highly dependent on cost of drilling, resource potential, and fluid enthalpy from production wells. LCOH from new wells is estimated to range from \$0.010 to \$0.014/kWh$_{th}$ (Table 6). The relatively high LCOH is related to the drilling cost. When an existing geothermal well is used, the LCOH can be lowered down to about \$0.005 to \$0.008/kWh$_{th}$ (Table 7). Accessing unused low-temperature heat from a geothermal power plant offers the potential to achieve costs in the range of \$0.003 to \$0.004/kWh$_{th}$, which reaches Kesieme's cost target for \$1/m^3 MD product water.

The cheapest source of thermal energy is excess heat coming from the outlet brine of geothermal power plants. In this case, capital costs include only a booster pump and interconnection piping, while operational costs include labor, re-injection pumping and chemical control (inhibitors). In the case of thermal-energy extraction from power-plant outlet brine, one should carefully investigate inhibitor optimization to prevent scaling and re-injection strategy for long-term production.

6 Cooling-Tower Blowdown as Source Water for Desalination

One potential source of water for desalination, especially in the West, is blowdown water from thermo-electric power plants with cooling towers. In these power plants, a heat source (e.g., fossil, nuclear, solar, or geothermal) vaporizes water to steam. The steam exiting the power turbine is condensed by cooling for reuse in the steam cycle. Recirculating cooling towers are often used in the arid West to minimize the required withdrawal rate of water for cooling. In wetter, more humid regions, once-through cooling is common.

At plants using cooling towers, the cooling loop circulates water between the condenser and cooling tower, as seen in Figure 17. As water evaporates, dissolved solids are left behind, increasing their concentration in the recirculating water. Some water has to be "blown down" or ejected to regulate the amount of dissolved solids and salts, which can accumulate in the pipes and tower packing and corrode the equipment. This blowdown water must be treated or disposed of in a safe manner. Alternatively, the water could be recaptured, desalinated, and recirculated to the plant. This would increase the water efficiency of these power plants and decrease the ecological effects of water withdrawal in these arid regions of the western U.S.

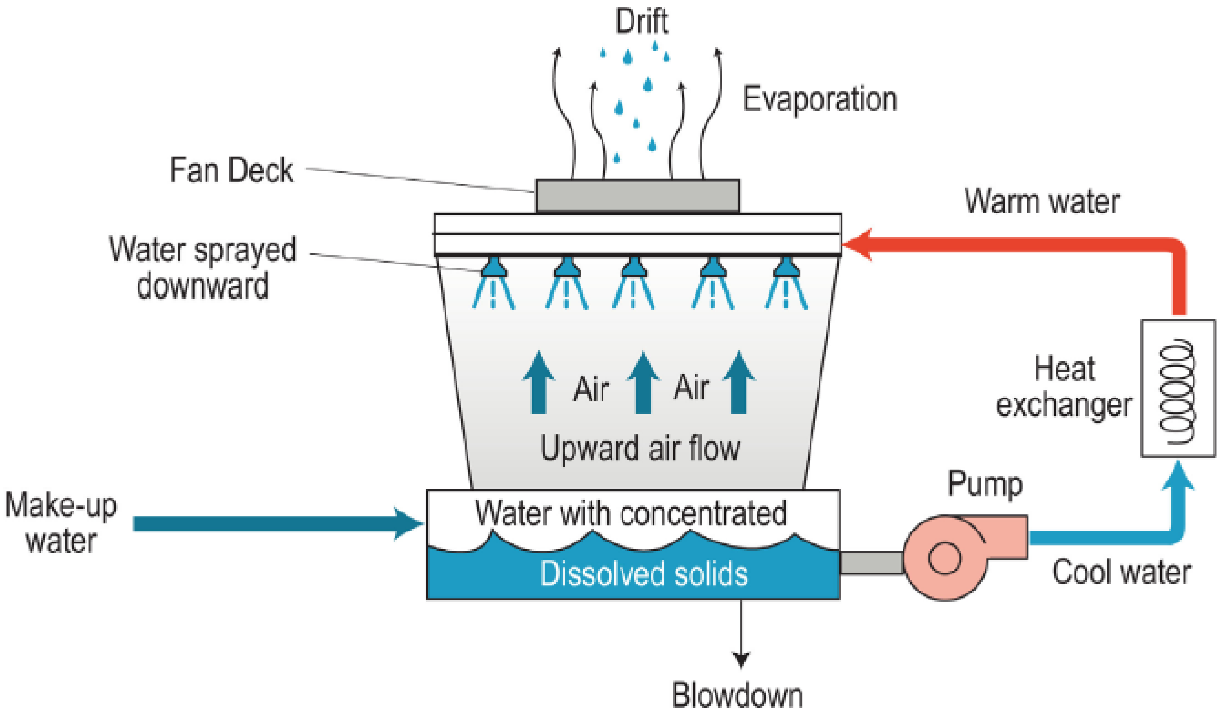


Figure 17. Typical configuration of a cooling tower at a thermo-electric power plant. The cooling-tower loop interfaces with the turbine's water/steam loop via a heat exchanger. Water consumption comes from evaporation, blowdown, and to a lesser extent, loss of water droplets as drift [23].

To assess the potential of blowdown-water desalination, this study accessed a database from the Union of Concerned Scientists that covered thermo-electric power plants across the United States [24]. The data were narrowed by selecting for plants that used wet-cooling towers in eight western states: Washington, Oregon, California, Idaho, Nevada, Utah, Arizona, and New

Mexico. The resulting 596 power plants were used to focus on the area of the western United States most impacted by long-standing droughts.

A preliminary estimate of blowdown flow volumes was made by calculating the difference between the "calculated withdrawal" and "calculated consumption," as reported within the database. This resulted in an estimated 60 billion gal/yr (616,000 m^3/day), but yielded zero blowdown for many of these power plants, which is an unrealistic result. It was assumed that these sites were using blowdown evaporation ponds and not discharging any water from the site.

Consequently, the amount of annual blowdown was estimated from the cooling load for the different types of power plants. The efficiency of energy conversion from fuel source to electricity differs for each power-plant type, and knowing these efficiencies allows one to estimate the cooling loads. Once the cooling load is known, the level of water usage is dependent on the *cycles of concentration* within the cooling tower (see Figure 18). Cycles of concentration refers to how many times the cooling water passes through the tower before being evaporated or rejected in the blowdown flow. Higher cycles use less water, but the concentration of dissolved solids in the cooling water will increase, which could lead to scaling and fouling problems.

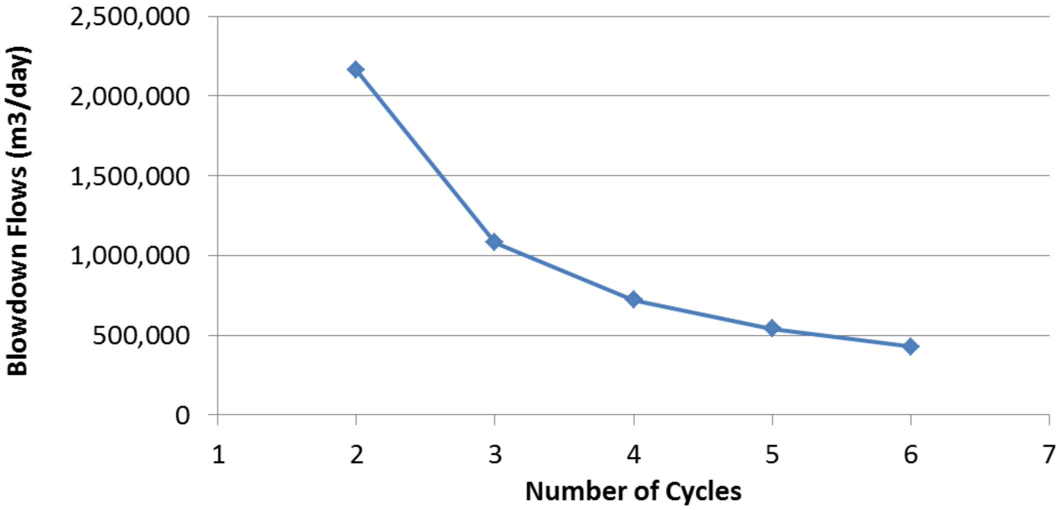


Figure 18. Total annual cooling tower blowdown volume for the eight western states in this study as a function of assumed cycles of concentration.

The power-plant database covered biomass, coal, geothermal, natural gas, nuclear, oil, and concentrating solar power (CSP) heat sources. The following assumptions were made as part of the calculation of blowdown water flows:

1. Power-plant thermo-electric efficiencies: biomass = 30%, coal = 35%, geothermal = 15%, natural gas combined-cycle = 55%, nuclear = 30%, oil = 35%, CSP = 35% [25]

2. Blowdown = Evaporation ÷ (Cycles of Concentration – 1) [26]

3. Cooling systems operating between two and six cycles of concentration [27].

Not all power plants operate at the same number of cycles of concentration, so a range was used of two to six cycles of concentration. The resulting blowdown estimates for the eight states range from 42 to 208 Bgal/yr (0.43 to 2.16 million m^3/day), as depicted in Table 8 and Figure 19. For reference, the city of Golden, Colorado (population ~20,000) uses about 1 Bgal/yr, so the opportunity presented by treating blowdown water could represent the water supply of up to 69 small cities, assuming 4 cycles of concentration.

Table 8. Estimated annual blowdown volume by state in billion gallons per year for different assumed cycles of concentration

Cycles of Concentration:	2 cycles	3 cycles	4 cycles	5 cycles	6 cycles
State					
WA	14.8	7.4	4.9	3.7	3.0
OR	5.9	3.0	2.0	1.5	1.2
CA	59.0	29.5	19.7	14.8	11.8
ID	1.2	0.6	0.4	0.3	0.2
NV	9.6	4.8	3.2	2.4	1.9
UT	31.6	15.8	10.5	7.9	6.3
AZ	74.1	37.0	24.7	18.5	14.8
NM	11.7	5.8	3.9	2.9	2.3
Total (billion gal/yr):	208	104	69	52	42
Total (m^3/day):	2,160,000	1,080,000	720,000	540,000	430,000

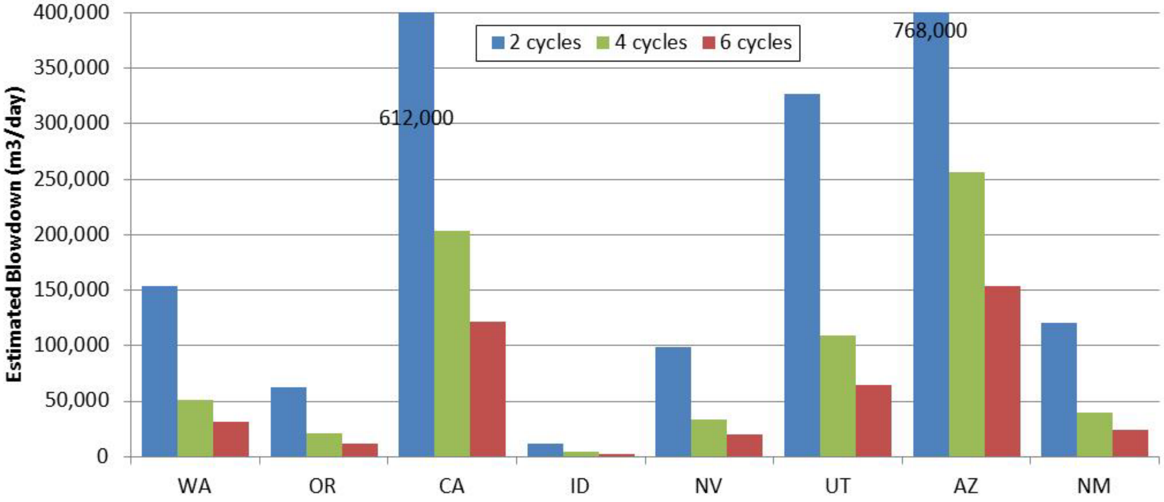


Figure 19. Estimated blowdown water volume as a function of assumed cycles of concentration for each western state.

Lastly, a map showing plant locations and estimated blowdown volumes assuming four cycles of concentration is shown in Figure 20. As a point of comparison, cooling-water requirements for geothermal power plants have been estimated at 2,000 gal/MWh (7.57 m^3/MWh), of which 1,400 gal (5.30 m^3) of water is evaporated and consumed during the cooling process and 600 gal/MWh (2.27 m^3/MWh) is discharged as blowdown [28]. Based on these numbers, blowdown water for a

10 MW$_e$ wet-cooled binary geothermal plant is estimated as 130,000 gal/day. Treating and making a portion of this water available for plant operations would reduce the cost to reinject the wastewater as well as avoid the cost of fresh water purchase.

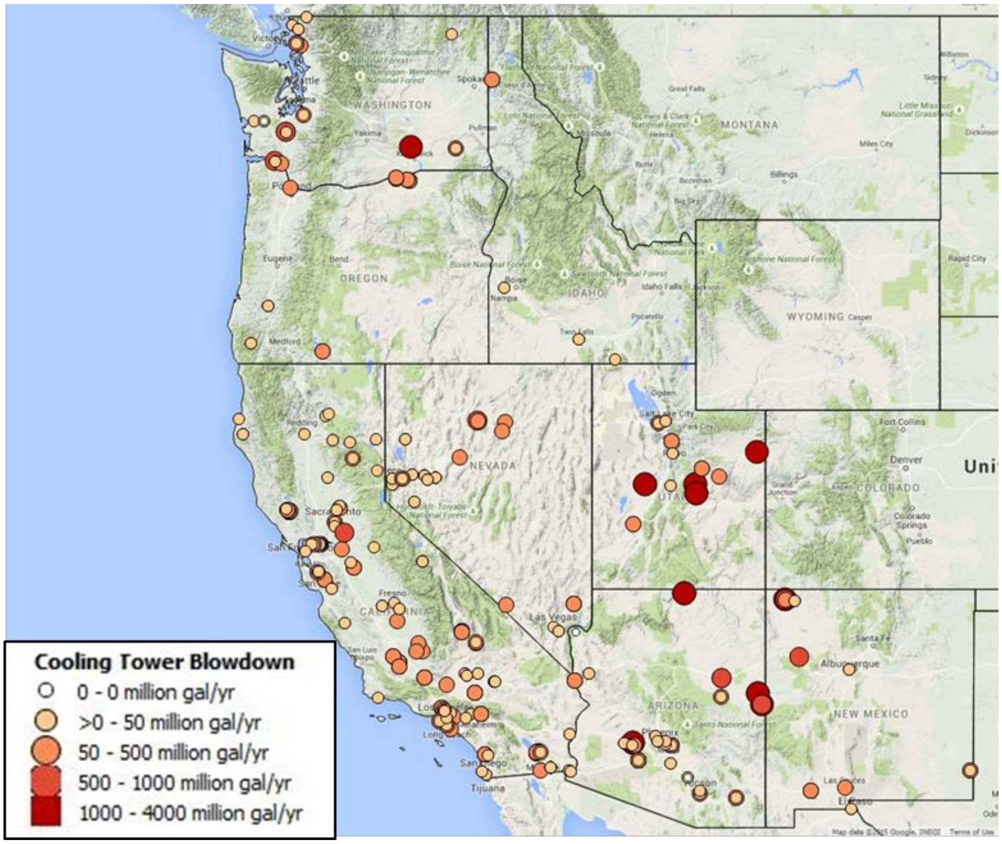


Figure 20. Google Maps overlay of thermo-electric power plants in the western United States that use cooling towers. The colors and sizes displayed represent estimated blowdown-water flow rates. © 2015 Google, Map Data

Discussion with geothermal developers identified cooling tower blowdown water as a source water of interest for desalination and reuse. The blowdown water is available onsite, must be disposed of, and could be processed with unused geothermal heat also available onsite. Production of a fresh water stream would offset water cost for staff operations at the site and could extend the cycles of concentration within the cooling tower loop.

7 Future Work

NREL, in collaboration with CSM and other partners, has proposed to pilot-test MD using geothermal energy. The overall goal of the project is to demonstrate the efficacy and to quantify the cost of using low-temperature geothermal resources to directly heat an MD system to produce high-quality water. The technology benefits will be quantified by the combination of avoided treatment/disposal cost of the source water and the value of the product water. A field test of geothermal-MD is expected to have the following outcomes:

- Demonstrate the integration of MD with geothermal energy,
- Develop a performance model and validate membrane flux estimates with commercial-scale modules under field conditions at different operating conditions,
- Demonstrate durability and performance of the membranes and membrane modules,
- Test and evaluate antiscaling and/or antifouling coatings applied to commercial membranes,
- Estimate cost of product water based on membrane performance and a sensitivity analysis to the cost of geothermal heat. Define conditions that lead to costs of less than $\$1/m^3$ or otherwise provide economic viability. Describe and quantify applications beneficial to the geothermal industry.

The proposed demonstration project includes two national laboratories, two universities, and two industry partners. Participants and primary responsibilities are listed in Table 9.

Table 9. Partners in the proposed geothermal-MD demonstration project

NREL	• Project management • Techno-economic and opportunity-potential analysis • Field-test support
Colorado School of Mines (CSM)	• Laboratory and field testing
Sandia National Laboratories	• Performance-model development
Univ. of California Riverside (UCR)	• Membrane coating and optimization
Ormat Technologies	• Potential site host and technology user
GE Power & Water	• MD technology developer/supplier

8 Conclusions

This joint project between NREL and the Colorado School of Mines has examined the potential of using low-temperature geothermal resources for desalination. The temperature range in question, less than about 100°C, is not well suited for electricity generation, but can be used for direct heating. Accordingly, the best integration approaches use thermal desalination technologies such as multi-effect distillation or membrane distillation, rather than electric-driven technologies such as reverse osmosis.

The examination of different desalination technologies led to the selection of MD for pairing with geothermal energy. MD operates at near-ambient pressure and temperatures less than 100°C with hydrophobic membranes. The technology is modular like RO, but the equipment costs are lower. The thermal-energy demands of MD are higher than MED, but this is offset by an ability to run at lower temperatures and a low capital cost. Consequently, a geothermal MD system could offer a low capital cost and, if paired with low-cost geothermal energy, a low operating cost. Literature reviews suggest product-water cost could be less than \$1/m^3 if thermal energy is inexpensive. Such a cost is competitive with the best desalination applications in the world. Furthermore, the MD technology is suited for small-scale installations, and although small plant capacity increases water cost per m^3, the scale is ideally suited for application in rural areas with modest-size geothermal resources.

The economics of desalination remain challenging regardless of technology. For example, 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. Product water from the new Carlsbad Desalination Project, a large RO plant in southern California, is expected to cost about \$1.7/m^3, which is stated to be about twice the cost of alternative water sources [19], [29]. Consequently, desalination is best applied where high-quality product water is valued and the impaired source water requires treatment for disposal. Such a situation provides two sources of "revenue" for the process—valuable product water and avoided treatment costs. The deployment of desalination as a hedge against future water scarcity, despite its relative cost, is sometimes listed as an additional supporting factor.

These "dual-revenue" conditions may exist for produced and flowback water from oil and gas operations, industrial wastewater, and locations where zero-water discharge is required or preferred. Thermal desalination processes can tolerate water of much higher TDS than RO systems, so locations striving for zero-discharge of wastewater or wishing to extract additional water from RO reject brine also would be amenable to geothermal desalination.

Based on these considerations, the treatment of cooling-tower blowdown water has been selected as an appealing application for demonstration of geothermal MD, and a potential site has been identified and proposed to the DOE GTO. The proposed project will access cooling-tower blowdown water at a geothermal power plant and use geothermal heat in a small-scale MD process. While this is a relatively small market opportunity, it is one of particular interest to the geothermal industry and provides a useful proving ground for the MD technology. Objectives include the following:

- Demonstrate the integration of MD with geothermal energy,

- Develop a performance model and validate membrane flux estimates with commercial-scale modules under field conditions at different operating conditions,

- Demonstrate long-term life and performance of the membranes and membrane modules,

- Test and evaluate antiscaling and/or antifouling coatings applied to commercial membranes, and

- Estimate cost of product water based on membrane performance and a sensitivity analysis to the cost of geothermal heat. Define conditions that lead to costs of less than $\$1/m^3$ or otherwise provide economic viability. Describe and quantify applications beneficial to the geothermal industry.

Based on low-temperature geothermal resource assessment estimates by the USGS [17], total resource capacity for identified hydrothermal systems having a mean reservoir temperature between 50°C and 90°C is more than 9,800 MW_{th}. USGS is revisiting this assessment, and an updated version will be released in late 2015 or 2016. In total, 13 states have potential for low-temperature hydrothermal resources (excluding sedimentary basins and enhanced geothermal systems), with Idaho, Nevada, Arizona, California, and Utah ranking as the highest potential. Other states with low-temperature geothermal potential are Montana, Alaska, Colorado, New Mexico, Wyoming, Texas, and Washington. At present, only a small portion of these resources are in use for direct-heat applications.

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Appendix

Appendix A – Objectives Categories used in GDsalt

Table A1. Monetary objectives cost categories and basis

Items	Remark/basis for facility capital cost estimation
Facility Capital Costs	
Treatment technology	Plant capacity
Pipelines	Pipe length and unit cost
Pump Stations	Flow rate, TDH lift, efficiency
Storage Facility	Storage type, volume, cost curves
Buildings	Capacity/flow rate
New Beneficial Use Infrastructure	Flow rate
Site Development Costs	% of capital costs
Yard Piping	% of capital costs
Electrical	% of capital costs
Annual Operations and Maintenance	
Energy Costs, treatment	Capacity, period of operation
Energy Costs, conveyance	Flow rate, TDH lift, efficiency, hours of operation/yr
Labor Costs, treatment facility	Salaries, wages
Chemicals; acid, base	Hours of operation/year, plant capacity, alkalinity(for acid)
Treatment Supplies	
Membrane costs	Annual replacement cost
Materials and Supplies	% of capital costs
Land lease	Typical BLM lease rate for one acre for one year
Other O&M costs	% of capital costs

Table A2. Non-monetary criteria

Description	Explanation
Operator oversight	Degree of operator oversight required
Ease of operation	Hazardous chemicals and operator skill required to manage the system
Flexibility	Ability of the technology to withstand highly variable water quality
Footprint	Size, in land area, that the process takes up
Industrial status	Market maturity, frequency of use, competitiveness of vendors
Chemical demand	Volume of chemicals required at the site
Energy demand	Specific energy required by the technology
Mobility	Ease of moving a technology from one part of the site to another
Modularity	Ability to implement a unit process and handle variable influent volume
Robustness	Ability to withstand varying environmental conditions
Waste management	Volume of waste and the technical skill required to handle it
Energy recovery	Ability to recover energy
Material recovery	The ability to recover materials

Appendix B – Beneficial-Use Water-Quality Requirements

Table B1. Beneficial-use water-quality requirements

Constituent	Units	Potable Use	Livestock	Crop Irrigation	Surface Water Discharge
Alkalinity (as $CaCO_3$)	mg/L				
Alkalinity-Bicarbonate	mg/L				
Alkalinity-Carbonate	mg/L				
Aluminum	mg/L		5.00	5.00	
Arsenic	mg/L	0.01	0.20	0.10	
Barium	mg/L	2.00			
Benzene	mg/L	5.00			
Boron	mg/L		5.00	1	2
Bromide	mg/L				
Calcium	mg/L				
Chloride	mg/L			70.00	1500
Chlorobenzene	mg/L				
Chromium, total	mg/L	0.10	1.00	0.10	
Copper	mg/L	1.30	1	0	0
Cyanide	mg/L	0.15			
Ethylbenzene	mg/L	0.70			
Ethylene Dibromide	mg/L				
Fluoride	mg/L	4.00	2.00	1.00	
Iron (II)	mg/L	0.30		5.00	5.00
Iron (III)	mg/L	0.30		5.00	5.00
Lead	mg/L	0.02	0.10	5.00	
Lithium	mg/L			15.00	
Magnesium	mg/L		250		
Manganese	mg/L	0.10	0.05	0.20	0.20
Mercury	mg/L				
Molybdenum	mg/L				
Nickel	mg/L			0.20	
Nitrate (as N)	mg/L		10.00		
Nitrite (as N)	mg/L				
Oil and Grease	mg/L				
o-Phosphate	mg/L				
Potassium	mg/L				
Radioactivity, Gross Alpha	pCi/L	15.00			
Radioactivity, Gross Beta	pCi/L	4.00			
Radium-226 + Radium-228	pCi/L	5.00			
Rd 226+222+228	pCi/L				
Selenium	mg/L	0.05	0.05	0.02	0.02
Silica (SiO_2)	mg/L				
Silver	mg/L				
Sodium	mg/L				
Specific Conductance	uS/cm				
Strontium	mg/L				
Sulfate	mg/L		1000		
TDS (calc)	mg/L	500	5000	1500	3500
Toluene	mg/L				
Total Nitrogen (as N)	mg/L		10.00		
Total Organic Carbon (TOC)	mg/L				
Total Petroleum Hydrocarbons	mg/L				
Total Suspended Solids (TSS)	mg/L				30.00
Uranium	ug/L	0.30			
Xylenes (total)	mg/L	10.00			
Zinc	mg/L		24.00	2.00	2.00

Appendix C – Sensitivity Analysis of GDsalt

Beyond the test cases described in the body text, additional test cases were analyzed using GDsalt to explore the sensitivity of the results to varying inputs. Two parameters were altered to demonstrate the functionality of GDsalt: percent water recovery and the criteria weighting for cost. GDsalt was tested at two water-recovery rates: 20% and 85%. Membrane processes are more sensitive to reject water TDS concentration than the thermal processes; thus, under higher water recovery, thermal processes should be preferentially selected depending on feed-water TDS concentration, everything else being equal. With lower water recovery, it is possible that membrane technologies are selected even for relatively high feed-water TDS values. Additionally, user-assigned criteria weights for capital and O&M cost were changed from the default value of 4 to a criteria weight of 1, thereby increasing the importance of these criteria. All other criteria weights were kept constant. The results of the sensitivity analysis are presented below.

The results demonstrated that GDsalt is sensitive to changes in percent water recovery, with lower water recovery leading to selection of membrane processes instead of thermal processes when feed-water concentration is not very high. GDsalt tends to suggest a membrane process unless limited by water recovery or high temperature mainly because the membrane processes cost less and are preferred in terms of many other criteria listed in Table A2.

GDsalt was not very sensitive to changes in weights assigned to capital and O&M costs; similar treatment trains were suggested regardless of the weights assigned to cost. (These scenarios are not presented in the Appendix). One reason for this result may be that the treatment selection was governed by performance constraints. Parametric and sensitivity analysis of GDsalt will continue to be explored in FY15.

The Imperial Valley groundwater test cases (Table C1) exhibited a wide range in TDS concentration. Consequently, this difference in TDS level dominated the selection, and the required water-recovery percentage did not affect technology selection. For the 25th-percentile case, GDsalt selected identical, non-thermal processes at both the 85% and 20% water recovery. The other two cases (mean and 75th-percentile source-water quality) had much higher TDS, which triggered selection of thermal processes irrespective of the recovery. Mechanical vapor compression remained an option for all cases.

Table C1. GDsalt results for Imperial Valley groundwater – effect of specified recovery

Source Water Imperial Valley Groundwater	85% Water Recovery		20% Water Recovery	
	Pretreatment	Desalination	Pretreatment	Desalination
25th percentile TDS = 1,500 mg/L	Media Filter	BWRO, SWRO, or MVC	Media filter	BWRO, SWRO, or MVC
Mean TDS = 195,000 mg/L	Chemical softening and media filter	MVC, MED, or TVC	Chemical softening and media filter	MVC, MED, or TVC
75th percentile TDS = 390,000 mg/L	Chemical softening and media filter	MVC, MED, or TVC	Chemical softening and media filter	MVC, MED, or TVC

Table C2 shows the result for Imperial Valley. GDsalt favored membrane processes at 20% water recovery and thermal processes for the 85% recovery, illustrating the transition caused by the specified level of water recovery. Mechanical vapor compression was a viable option under both conditions.

Table C2. GDsalt results for Imperial Valley – effect of specified recovery

Imperial Valley Source Water	85% Water Recovery		20% Water Recovery	
	Pretreatment	Desalination	Pretreatment	Desalination
Surface Water TDS = 44,100 mg/L	Acid cation IX (H), Media filter GAC	MVC, MED, or TVC	Acid cation IX (H), Media filter GAC	BWRO, SWRO, or MVC
Geothermal Brine TDS = 195,000 mg/L	Media filter and Acid cation IX (H)	MVC, MED, or TVC	Media filter and Acid cation IX (H)	BWRO, SWRO, or MVC

Table C3 lists the cases for Hidalgo County, TX. The groundwater TDS was relatively low, less than 5,400 mg/L for all cases; thus, the tool selected membrane processes for all cases. The results of the Hidalgo County surface-water case mimicked that for the 25th-percentile Imperial Valley groundwater case, which also had a relatively low TDS level.

Table C3. GDsalt results for Hidalgo County, TX groundwater – effect of specified recovery

Source Water Hidalgo County Groundwater	85% Water Recovery		20% Water Recovery	
	Pretreatment	Desalination	Pretreatment	Desalination
25th percentile TDS = 1,300 mg/L	Media filter	BWRO, SWRO, or MVC	Media filter	BWRO, SWRO, or MVC
Mean TDS = 3,300 mg/L	Media filter	BWRO, SWRO, or MVC	Media filter	BWRO, SWRO, or MVC
75th percentile TDS = 5,400 mg/L	Media filter	BWRO, SWRO, or MVC	Media filter	BWRO, SWRO, or MVC

Appendix D – Case Study Provided to CSM Senior Design Class

Design of a Geothermal Desalination Process for Potable-Water Production

Project Overview: Geothermal resources and water scarcity are two common features of the western United States. Low-temperature (< 100°C) geothermal resources have wide geographic distribution, but are highly underutilized because they are too inefficient for power production. A potentially useful application of low-enthalpy geothermal energy—from low-temperature resources or rejected heat from high-temperature geothermal power plants—is the desalination of impaired waters (e.g., brackish surface or groundwater, seawater, or brines co-produced from oil and gas operations). Desalination of impaired water has the potential to mitigate the substantial declines in western water resources that have been observed in the last few decades.

This study will explore if heat from low-enthalpy geothermal sources can either be directly utilized in thermal desalination processes (e.g., multi-effect distillation) or indirectly used to generate small-scale power generation necessary for electricity-based desalination processes (e.g., nanofiltration (NF) or reverse osmosis (RO)). The project will include interaction with engineers at the National Renewable Energy Laboratory (NREL) and CSM's Advanced Water Technology Center.

Selection of water-desalination processes is a complex task, and it can include dozens of desalination and pretreatment technologies. It involves the development of a treatment train that comprises a desalination technology and pretreatment process (in both cases, there can be one or more technologies) based on input water composition and quantity and the desired end-use water quality. A computerized decision support tool is a good way to "automate" this process to identify the best candidate treatment technologies and trains based on parameters such as water quality, treatment efficiency, available energy, energy-demand limitations, and overall economics (i.e., capital and O&M costs). A joint project between NREL and CSM has developed GDsalt, a geothermal desalination decision tool. This project will use GDsalt and NREL's geothermal exploration and analysis tools to aid in the design of a treatment system to produce potable water from brackish water in the western U.S.

Project Deliverables: The study will examine desalination of brackish groundwater and/or surface water in California's Imperial Valley—a region with severe water shortages and strong geothermal resources. A substantial amount of support material is available for this project. Your team will simulate water-treatment trains in Aspen based on the suggestions of GDsalt. The objective is to simulate each of the water-treatment processes in the train and the entire treatment train, analyze thermal-energy demands, electric-energy demand, and the economic viability of the processes.

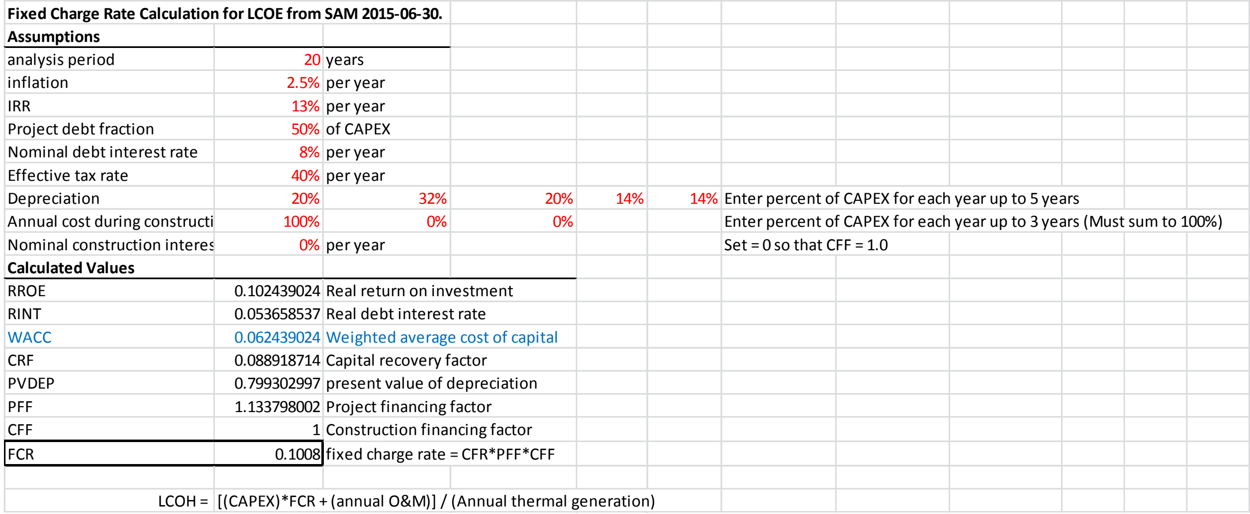
Tasks to be completed in this assignment include:

- Learn to operate GDsalt and generate water-treatment trains combining thermal and electrical energy from geothermal power plants (responsibility of CEE). NREL staff will assist the team with the usage of NREL's System Advisor Model and Geothermal Prospector to estimate geothermal system cost.

- Generate detailed process designs for one base case at several water-recovery rates (increasing water recovery from the same source of water, leading to higher concentration of the brine), including detailed water and energy flows, product recovery, and waste generation.
- Complete detailed ASPEN simulations for the treatment train.
- Propose and evaluate two alternative designs that improve the process efficiency, utilization of geothermal thermal energy, and/or maximize clean-water recovery/production.
- Estimate capital and operating costs for the base-case design and two options (20-year economic life) for a facility to produce potable water. Provide installed system cost and cost per unit of product water.

Appendix E – Calculation of Levelized Cost of Heat

The LCOH is calculated in a spreadsheet using the formulae for fixed charge rate (FCR) as described in SAM version 2015-06-30, which is based on reference [29]. The explanation below is excerpted from SAM's help menu.



Fixed Charge Rate Calculation for LCOE from SAM 2015-06-30.						
Assumptions						
analysis period	20	years				
inflation	2.5%	per year				
IRR	13%	per year				
Project debt fraction	50%	of CAPEX				
Nominal debt interest rate	8%	per year				
Effective tax rate	40%	per year				
Depreciation	20%	32%	20%	14%	14%	Enter percent of CAPEX for each year up to 5 years
Annual cost during constructi	100%	0%	0%			Enter percent of CAPEX for each year up to 3 years (Must sum to 100%)
Nominal construction interes	0%	per year				Set = 0 so that CFF = 1.0
Calculated Values						
RROE	0.102439024	Real return on investment				
RINT	0.053658537	Real debt interest rate				
WACC	0.062439024	Weighted average cost of capital				
CRF	0.088918714	Capital recovery factor				
PVDEP	0.799302997	present value of depreciation				
PFF	1.133798002	Project financing factor				
CFF	1	Construction financing factor				
FCR	0.1008	fixed charge rate = CFR*PFF*CFF				
LCOH =	[(CAPEX)*FCR + (annual O&M)] / (Annual thermal generation)					

SAM's LCOE Calculator uses a simple method to calculate a project's levelized cost of energy (LCOE) using only the following inputs:

- Total Capital Cost, $ (TCC)
- Fixed annual Operating Cost, $ (FOC)
- Variable Operating Cost, $/kWh (VOC)
- Fixed Charge Rate (FCR)
- Annual electricity production, kWh (AEP)

The LCOE Calculator uses the following equation to calculate the LCOE:

$$\mathrm{LCOE} = \frac{\mathrm{FCR} \times \mathrm{TCC} + \mathrm{FOC}}{\mathrm{AEP}} + \mathrm{VOC}$$

The fixed charge rate is the revenue per amount of investment required to cover the investment cost. For details, see pp. 22-24 of reference [29]. This method is an alternative to the cash flow method used by SAM's other financial models. It is appropriate for very preliminary stages of project feasibility analysis before you have many details about the project's costs and financial structure. SAM does not contain a geothermal hybrid model, so direct use of SAM's other financial models is not possible.

Capital and Operating Costs

Capital cost

The project's total investment cost.

Fixed operating cost

Annual operating costs that do not vary with the amount of electricity the system generates.

Variable operating cost

Annual operating costs in dollars per kilowatt-hour that vary with the amount of electricity the system generates.

Summary

The Summary values are the inputs to the LCOE equation. These values are calculated from the inputs you specify.

Fixed charge rate

The project fixed charge rate, or revenue per amount of investment required to cover the investment cost. Calculated from the financial details you enter.

Capital cost

The total overnight investment cost in dollars.

Fixed operating cost

The fixed annual operating cost in dollars. It is either the value you enter or a value that SAM calculates based on the value you enter in dollars per kilowatt.

Variable operating cost

The variable annual operating cost in dollars per kilowatt-hour that you enter.

Financial Assumptions

The fixed charge rate represents details of the project's financial structure.

Calculate fixed charge rate

SAM calculates the fixed charge rate from a set of financial assumptions. SAM uses the following equation to calculate the value from the capital recovery factor, project financing factor, and construction financing factor (see below for all equations):

$$\mathrm{FCR} = \mathrm{CRF} \times \mathrm{PFF} \times \mathrm{CFF}$$

Fixed charge rate

The project's fixed charge rate. Note that the value is a factor (between 0 and 1) rather than a percentage.

Analysis period

The number of years that the project will generate electricity and earn revenue.

Inflation rate

The annual inflation rate over the analysis period.

Internal rate of return

The project's annual rate of return requirement.

Project term debt

The size of debt as a percentage of the capital cost.

Nominal debt interest rate

The annual nominal debt interest rate. SAM assumes that the debt period is the same as the analysis period.

Effective tax rate

The total income tax rate. For a project that pays both federal and state income taxes, where the state income tax is deducted from the federal tax, you can calculate the effective tax rate as:

$$\mathrm{TAX} = \mathrm{STATE} + \mathrm{FED} \times (1\text{-}\mathrm{STATE})$$

Depreciation schedule

The annual depreciation schedule. The depreciation basis equals the project's capital cost.

Annual cost during construction

The annual construction cost as a percentage of the project's capital cost. If the construction period is one year or less, enter a single value. If it is more than one year, enter a schedule of annual percentages.

Nominal construction interest rate

The annual interest rate on construction financing.

Capital recovery factor (CRF)

SAM calculates this value from the inputs you specify as described below.

Project financing factor (PFF)

Factor to account for project financing costs. SAM calculates this value from the effective tax rate and depreciation schedule, as described below.

Construction financing factor (CFF)

Factor to account for construction financing costs. SAM calculates the value from the construction cost schedule, effective tax rate, and construction interest rate, as described below.

Equations for FCR Calculation

When you use the **Calculate fixed charge rate** option, SAM uses the following equations to calculate the financing factors.

Nomenclature

c = Construction year

C = Construction period in years

CON = Construction schedule

DF = Project term debt fraction

i = Inflation rate

n = Analysis year

N = Analysis period

IRR = Nominal return on investment

NINT = Nominal debt interest rate

PVDEP = Present value of depreciation

RINT = Real debt interest rate

RROE = Real return on investment

TAX = Effective tax rate

WACC = Weighted average cost of capital (real)

The capital recovery factor (CRF) is a function of the weighted average cost of capital (WACC) and analysis period (N):

$$\mathrm{CRF} = \frac{\mathrm{WACC}}{1-\frac{1}{(1+\mathrm{WACC})^{N}}}$$

Where:

$$\mathrm{WACC}=\frac{1+\left((1\text{-}\mathrm{DF})\times\left((1+\mathrm{RROE})\times(1+i)\text{-}1\right)\right)+\mathrm{DF}\times\left((1+\mathrm{RINT})\times(1+i)\text{-}1\right)\times(1\text{-}\mathrm{TAX})}{1+i}\text{-}1$$

$$\mathrm{RROE}=\frac{1+\mathrm{IRR}}{1+i}-1$$

$$\mathrm{RINT}=\frac{1+\mathrm{NINT}}{1+i}-1$$

The project financing factor (PFF) is a function of the effective tax rate and depreciation schedule:

$$\mathrm{PFF}=\frac{1\text{-}\mathrm{TAX}\times\mathrm{PVDEP}}{1\text{-}\mathrm{TAX}}$$

Where:

$$\mathrm{PVDEP} = \sum_{n=0}^{N}\frac{\mathrm{DEP}_n}{\left((1+\mathrm{WACC})\times(1+i)\right)^{(n+1)}}$$

The construction financing factor (CFF) is a function of the construction cost schedule, effective tax rate, and nominal construction financing interest rate:

$$\mathrm{CFF}=\sum_{c=0}^{C}\mathrm{CON}_c\times\left(1+(1\text{-}\mathrm{TAX})\times\left((1+\mathrm{CINT})^{(c+0.5)}-1\right)\right)$$