*Desalination and Water Treatment*
www.deswater.com
doi: 10.1080/19443994.2016.1144693

57 (2016) 23110–23118
October

Taylor & Francis
Taylor & Francis Group

# Geothermal electricity generation and desalination: an integrated process design to conserve latent heat with operational improvements

Thomas M. Missimer[a,b,*], Kim Choon Ng[b,c], Kyaw Thuw[b,c], Muhammad Wakil Shahzad[b,c]

[a]*U. A. Whitaker College of Engineering, Florida Gulf Coast University, 10501 FGCU Boulevard South, Fort Myers, FL 33965-6565, USA, Tel. +1 966 012 808 4964; email: tmissimer@fgcu.edu (T.M. Missimer)*
[b]*Water Desalination and Reuse Center, King Abdullah University of Science and Technology, Thuwal 23955-6900, Saudi Arabia*
[c]*Department of Mechanical Engineering, National University of Singapore, Singapore*

Received 28 January 2015; Accepted 14 January 2016

**ABSTRACT**

A new process combination is proposed to link geothermal electricity generation with desalination. The concept involves maximizing the utilization of harvested latent heat by passing the turbine exhaust steam into a multiple effect distillation system and then into an adsorption desalination system. Processes are fully integrated to produce electricity, desalted water for consumer consumption, and make-up water for the geothermal extraction system. Further improvements in operational efficiency are achieved by adding a seawater reverse osmosis system to the site to utilize some of the generated electricity and using on-site aquifer storage and recovery to maximize water production with tailoring of seasonal capacity requirements and to meet facility maintenance requirements. The concept proposed conserves geothermally harvested latent heat and maximizes the economics of geothermal energy development. Development of a fully renewable energy electric generation-desalination-aquifer storage campus is introduced within the framework of geothermal energy development.

*Keywords:* Geothermal energy electricity generation; Multiple effect distillation; Adsorption desalination; Seawater reverse osmosis desalination; Aquifer storage and recovery

## 1. Introduction

Most renewable energy methods for electricity generation cannot be used to provide base-load into the grid system (e.g. solar and wind generation) and also suffer a number of inefficiencies in the generation process. Electricity generation using geothermal energy harvesting does provide a base load to the grid, but commonly is not very efficient because of wasted latent heat occurring after steam passage through the turbine. The steam passing through the turbine is commonly vented to ambient after the first or second cycle with no additional beneficial use or is condensed to produce process water for reuse.

*Corresponding author.

*Presented at EuroMed 2015: Desalination for Clean Water and Energy Palermo, Italy, 10–14 May 2015. Organized by the European Desalination Society.*

1944-3994/1944-3986 

Many current geothermal electric generation facilities extract hot water/steam from wells which is converted to electricity using direct dry steam or the single-flash steam process [1]. The mixture of steam and liquid produced by wells is separated into two phases using a cylindrical cyclone pressure vessel [2]. The vessel is commonly oriented in a vertical configuration wherein the phases separate due to their relative density difference. Although many of these systems have been successfully operated for decades, such as in Iceland, Indonesia, Japan, and New Zealand, the development of potential geothermal resources of this type is geographically restricted to locations with unique geologic characteristics (e.g. volcanic and permeable aquifers) and has a range of aquifer water temperatures ranging from 80 to 150˚C [1–7]. Capture and use of water/steam from geothermally heated aquifers is not always a renewable resource and most heat reservoirs have a finite life-expectancy based on a higher heat harvesting rate vs. the heat flux into the system. The imbalance of the heat or water budget limits the useful life of the resource.

Another approach to geothermal energy production is the utilization of hot dry rock heat (HDR) reservoirs. Large regions of the world contain HDR at depths ranging from 1 to 5 km beneath surface with corresponding temperatures ranging from 100 to 350˚C with even greater temperatures below 5 km [8–12]. A considerable amount of theoretical analysis and experimental work has been conducted on HDR geothermal electricity generation, particularly in the United States at the Fenton Hill site located in New Mexico, and in other countries (China, Australia) [8,12–16]. However, the capital cost and investment return on these systems is somewhat problematical compared to lower cost conventional electricity generating systems based on some past economic analyses (global warming issue not considered) [11,17,18]. One of the several factors that influence cost is the necessity of producing ultra-pure water for use in the injection and recovery well system [15]. In order to provide a more favorable economic return, another income stream could be generated, such as desalination of seawater, which would also be a source of the required ultra-pure water for the geothermal heat extraction system.

Geothermal-powered desalination has been investigated on a theoretical basis for many years with the concept of using pre-heated water from thermal springs or hot groundwater for either indirect desalination with electric generation first or direct desalination by heating the feedwater [19–25]. Some geothermal desalination systems have been constructed and are operating, but mostly are low-enthalpy systems with small capacities [26–30]. The concept of linking geothermal-generated electricity and desalination at a large scale has been previously suggested [24,31]. While the low-enthalpy geothermal systems do provide a renewable energy source that can facilitate desalination processes, they cannot produce the necessary water temperatures, in most cases, to properly heat feedwater to meet the needs of conventional thermal desalination technologies, such as multi-stage flash distillation (MSF) or multiple-effect distillation (MED). Developing desalination technologies, such as thermal distillation (TD) and adsorption desalination (AD) can be directly powered using geothermal (hot water) systems for heating the feedwater [32–34]. Seawater reverse osmosis (SWRO) desalination cannot be directly powered by geothermal energy and must use electricity generated from some type of power plant.

The objectives of this research are to fully integrate geothermal electricity generation using a HDR source with multiple seawater desalination process trains to improve system operational efficiency as proposed in a recent patent filing by the authors [35]. The improvement in operational efficiency and the revenue stream from sale of potable water will produce an improved economic return from geothermal energy development. Two thermal heat desalination processes have been linked to the electricity generation to conserve the latent heat harvested from the geothermal system, thereby making the entire system more efficient and improving the cost-benefit ratio for using geothermal energy. SWRO has also been co-located on-site along with additional storage (aquifer storage and recovery (ASR)) to produce a geothermal-electricity generation-desalination-storage water campus.

## 2. Methods

Research was conducted on the configuration of existing electricity generation facilities with emphasis on the efficient use of stream obtained from a geothermal source and a new scheme was developed to link thermal desalination processes with the steam turbine system discharge to maximize the conservation of latent heat through the system. In addition, the fully integrated electric generation and desalination system was further incorporated into the operation of the closed-loop geothermal heat collection system to provide the required make-up water. This heat cycling process was assessed to determine the best operational steam temperature to achieve efficient electric generation and desalination. Further, a SWRO desalination system was linked to the electric generation on the same site along with an ASR system to demonstrate the concept of a geothermal electric generation-desalination-water storage "campus" with the objective of achieving full operational flexibility to meet seasonal fluctuations in water demand, scheduled maintenance of facilities, and emergencies caused by equipment failure or other crises.

The specific inefficiencies being addressed are: (1) wasted latent heat vented to ambient in standard geothermal electric generation designs, (2) imbalances between electric demand and generation capacity, (3) imbalances between desalination capacity and treatment capacity of a desalination plant, and (4) reduction in maintenance down time with regard to electricity generation and/or desalination. The desired multiple process design would need to address each of these issues in a comprehensive and integrated manner.

## 3. Results

### 3.1. Electric generation from HDR source

Conventional electric generation from a geothermal water and/or steam source requires a minimum temperature of about 150°C [36,37]. Current drilling technology does allow borehole penetration to depths at which temperatures can exceed 500°C. Rock and fluid temperatures in many petroleum and gas reservoirs exceed 300°C, such as in the Haynesville Shale in East Texas and North Louisiana where the temperature at 3,600 m ranges between 260 and 380°C [38]. At the HDR test site in New Mexico, the bottom hole temperature at 4,600 m below land surface was 320°C [15]. While it is possible to develop an HDR geothermal heat harvesting scheme to produce water at quite high temperatures, a critical issue likely to limit the operational water temperature is the supercritical state of water at 374°C. Production of water above this temperature could lead to geochemical mobilization of a variety of dissolved substances, such as silica, that could lead to undesired scaling that would necessitate some type of expensive treatment system [39].

HDR geothermal energy development involves the construction of two or more deep wells having designated injection and recovery functions (Fig. 1). To improve subsurface heat exchange efficiency, the hot rock body could be developed by drilling a well containing a horizontal offset and then hydraulically fracturing the rock as suggested by Brown et al. [15]. The horizontal part of the injection well is hydraulically fractured to increase the apertures of natural fractures and to create new fracture permeability for more efficient heat exchange and transmission to the recovery well. The paired recovery well(s) is drilled into the fractured rock, intersecting it at a right angle so the vertical borehole gathers the heated water passed through the fractures. The lower part of the recovery well may require hydraulic fracturing to achieve a more direct connection to the fractures created in the

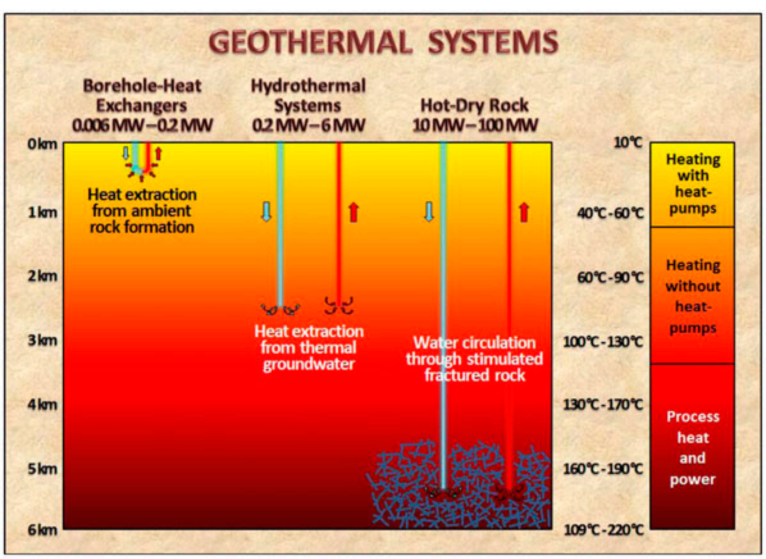


Fig. 1. Geothermal energy extraction systems with the HDR shown on the right side of the diagram. Note that the injection well is drilled with a horizontal offset and hydraulic fracturing is required to open the apertures of natural fractures and to create new fracture to enhance the permeability and increase the surface area to promote a higher heat exchange rate.

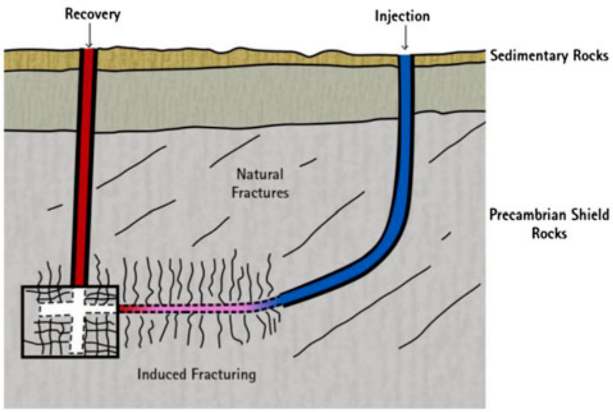


Fig. 2. Diagram showing the geometry of a horizontal offset well that has been hydraulically fractured with a vertical recovery well that has also been hydraulically fractured. The intersections of fractures within the effective hydraulic collection radius of the recovery well is improved allowing more efficient flow of water through the closed loop.

horizontal offset because these induced fractures will have an essentially vertical orientation. By fracturing the vertical recovery well borehole, a series of fracture intersections are achieved at right angles (Fig. 2).

The closed-loop geothermal heat recovery system operates by pumping distilled water (cool) into the injection well under pressure. Heat exchange occurs in the fractures within the horizontal offset. The heated water then enters the recovery well and is conducted under pressure to land surface, where the superheated water is allowed to flash to steam in front of the turbine. The desired temperature of the steam ranges between 250 and 300˚C. The make-up water from the closed loop heat collection systems would be obtained from one or both of the thermal distillation processes being operated. The proposed system stream temperature at the well head is 180˚C for the integrated design scheme. It is possible than a steam/water separation unit may be required before the electric generation turbine.

### *3.2. Integration of the thermal desalination processes with electric generation*

A considerable quantity of super-heated steam will discharge from the electric generating turbines for either regeneration (second cycle) or venting to ambient. Some of the steam could be regenerated (by reheating) for additional electric generation by passing through another turbine and all or some of the stream could be allowed to pass downstream into the thermal desalination processes. Electric generation/desalination hybridization is already becoming a common practice in the Middle East with associated gains in energy efficiency [40,41] and additional improvements in process integration will tend to reduce the overall energy use and cost of desalination [42]. However, further integration of the electric generation and thermal desalination processes can be achieved. If it is assumed that the discharge steam after passing through the electric generation turbine is still at about 140˚C, then the loss of energy is quite significant. An example of a typical geothermal flash steam electric generation plant of 10 MW capacity is shown in Fig. 3. The estimates percentages for 1 unit of heat extracted from the HDR well can be calculated for various efficiency issues. These values are given in Table 1.

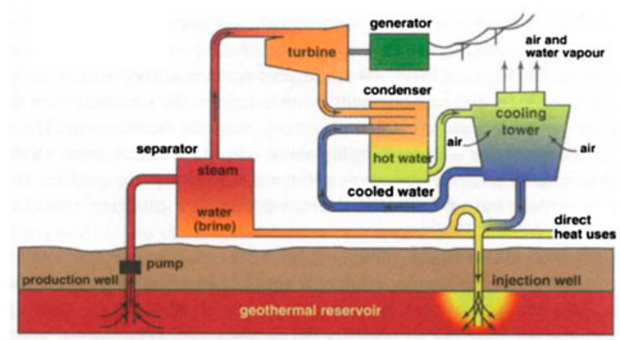


Fig. 3. Geothermal flash steam electrical generation plant (from Stober and Bucher [43]). Note that wasted latent heat is discharged through the cooling tower.

Table 1
Estimated percentages for a nominal 10 MW extracted heat from the HDR well

| Item | Efficiency percentage | Units (kW) |
|---|---|---|
| 1. Effectiveness of flashed chamber | 0.85 | 8,500 |
| 2. Isentropic efficiency of low-pressure steam turbines | 0.78 | – |
| 3. Electricity produced by steam turbines | 0.663 | 6,630 |
| 4. Work ratio of geothermal plant (defined as a ratio of electricity consumed to electricity produced) | 0.2 | 1,326 |
| 5. Net electricity output | 0.53 | 5,304 |
| 6. Fraction of heat supplied to district heating | 0.1 | 1,000 |
| 7. Overall efficiency of geothermal power | (0.53 + 0.1)/1 = 0.63 | 6,304 |

Hot steam vented from the turbine would first be directed into a heat exchanger system that would heat the feedwater for a multiple-effect (MED) desalination system (Fig. 4). This system would operate efficiently at a steam inlet and outlet temperature of 200 and 100°C, respectively. The steam temperature at the head of the MED process would be 100°C which would sustain the top-brine temperature (TBT) at 65–70°C. There could be several steam heating applications occurring in the downstream MED process, such as the AD cycle. Therefore, a side-stream pipe could be used to direct some steam to the re-heating end of the process (Fig. 5). A second source of latent heat is contained within the discharge water from the MED process. This water would have a temperature of about 5–10°C. However, the enthalpy of the vapor is

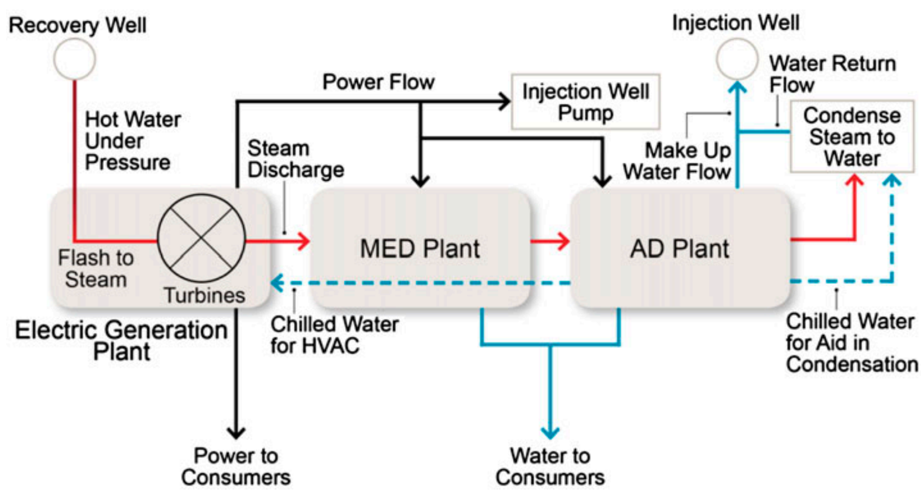


Fig. 4. Schematic diagram showing the HDR geothermal energy development system used to generate electricity and desalinate seawater. Note that the captured heat in the form of steam passes through the generation turbines and through two desalination processes before it is condensed to water for reinjection. The processes within the facility are fully integrated to maximize efficiency by conservation of latent heat.

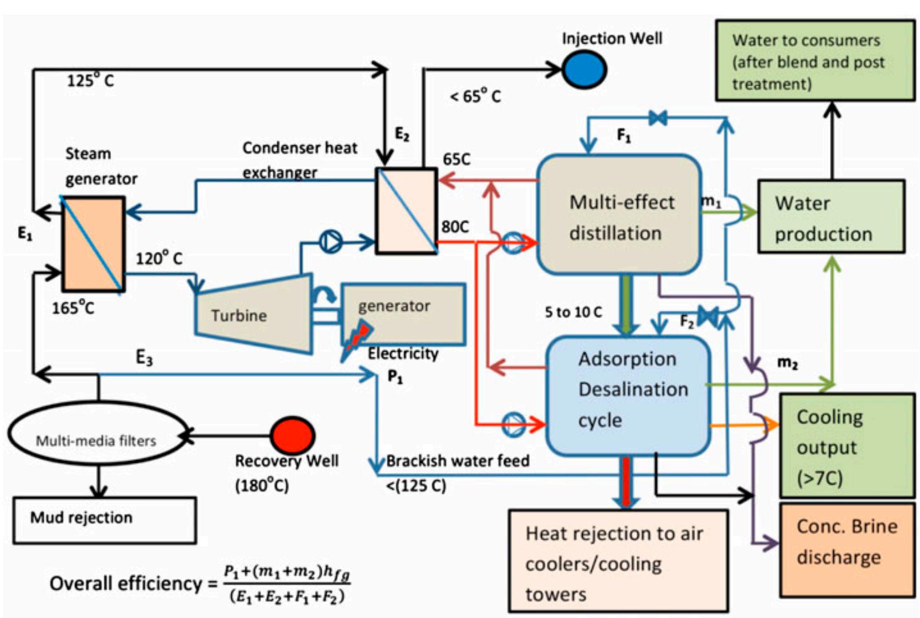


Fig. 5. Diagram showing the diversion of steam through side-stream pipes to assist in the MED process.

not condensed, but would be recirculated back into the MED cycle for more water production with the aid of a steam-driven ejector compressor.

The cooled steam leaving the MED process would still have some remaining latent heat that could become the energy source for operation of an AD system or a membrane distillation (MD) system. AD systems require lower operating temperatures in the range of 65–90˚C [44–46]. Recently, the full integration of MED-AD systems has been suggested as a means of reducing the energy consumption and overall cost of thermal desalination [47,48]. MD is another thermal desalination system that requires relativity low feedwater temperatures for successful operation [34,49–53]. The MD process could also be used in the downstream thermal desalination processes as a substitute for AD or along with AD. However, the cooling function of AD creates another full system synergy within the overall process.

AD desalination technology produces two useful product streams, desalted water and chilled water [54–56]. The chilled water stream is also useful within the full facility integration for the HVAC system in all onsite facilities and to facilitate condensing of the remaining steam for use in the closed-loop geothermal heating collection system. Also, operational adjustments can be made on the AD system to control the desired production rate of desalted water vs. the rate of chilled water production. This would be of considerable value based on seasonal changes in water demand and required HVAC loading rates.

### 3.3. Creation of a geothermal-driven electric generation-desalination-storage campus

Linkage and integration of the geothermal-generated electric generation with the two thermal desalination processes does achieve a significant degree of improvement in energy utilization, but there are additional operational efficiencies that can be obtained. The co-location of a SWRO water treatment plant and a treated water ASR system would reduce the overall energy consumption for desalination because the RO process uses significantly less energy for seawater conversion (Fig. 6) [57,58]. Also, SWRO commonly produces water in some regions (e.g. the Arabian Gulf and Red Sea) that does not meet drinking water standards because of the high total dissolved solids concentration in the feedwater. By co-locating the thermal desalination and SWRO facilities, the product waters can be blended to meeting the drinking water standard and reduce post-treatment costs of the very pure thermally desalted water.

An additional degree of operational efficiency and a higher degree of water security can be achieved by locating an ASR system on the site to achieve a complete "geothermally-driven energy/water campus." The link between operational ASR and desalination processes has been previously suggested [59–61], but

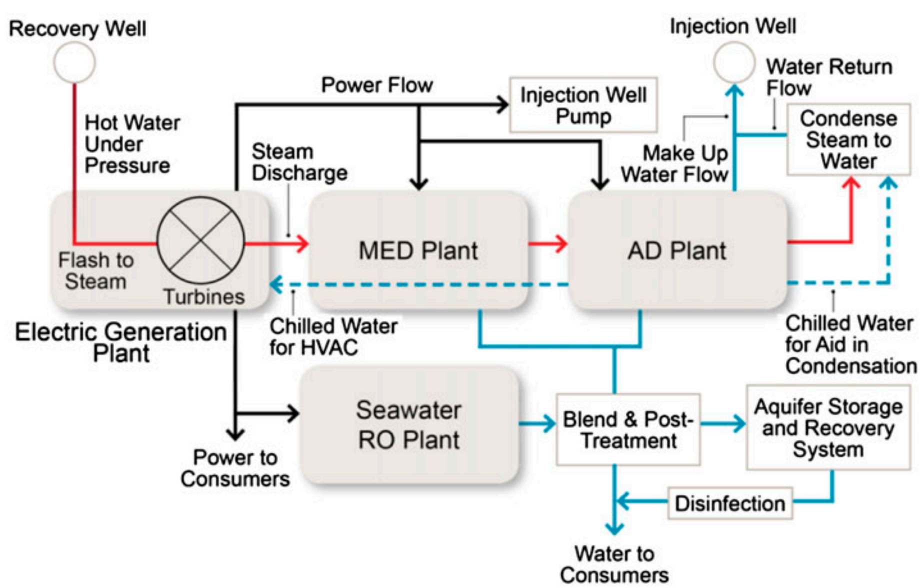


Fig. 6. Improvement of operational efficiency and reduction in overall desalination costs can be further improved by adding the SWRO process and ASR. This allows better system integration.

not linked with geothermal energy development. Water from the three on-site treatment process facilities would be pumped into the ASR system for storage when there is excess capacity and recovered when needed to meet peak demands, for water security, for emergency use, and during facility maintenance cycles. The ASR system allows maintenance to be performed on any component of operation without interruption of potable water flow to the distribution system. Facilities optimization can be achieved and the methods of operation "tuned" to any set of conditions that may occur with the ability of making adjustments in time as conditions change.

## 4. Discussion

It is a goal of all researchers in desalination to reduce the energy consumption in the desalination process which, in turn, reduces the carbon footprint. By coupling geothermal electric generation with multiple desalination processes and storage, a facility will operate as a fully renewable energy system that provides both electricity and potable water. While many researchers and design engineers have developed hybrid systems linking electric generation with desalination, little attention has been given to full integration of multiple processes to maximize operational efficiency. The full integration of geothermal derived heat, in the form of combined steam and hot water, with electric generation and thermal desalination processes is new and has considerable merit using the concept of latent heat conservation. In many cases, the generation of electricity using geothermal energy vents the waste steam to ambient causing the loss of harvested latent heat that can be used to desalt seawater using downstream processes. The loss of energy is roughly equivalent to a loss of 5–7% of electric generation capacity with an ambient steam discharge temperature of less than 140°C.

The fundamental concept is to arrange the desalination processes in a configuration that requires lesser energy (heat) in the downstream direction, therefore using as much of the geothermally harvested latent heat as possible. Also, increased operational efficiencies may be achieved by using side streams of steam to apply to appropriate parts of the thermal desalination processes. Using AD as the terminal thermal desalination process provides another operational advantage created by the ability of the process to produce chilled water which can be utilized in several different ways including facility air conditioning and in aiding condensation of the remaining steam to obtain process water from the geothermal heat recovery system.

Co-locating a SWRO facility with the MED and AD units provides another reduction in the overall production cost for desalting water. Electricity can be conducted directly to the SWRO plant using a very short transmission connection. Water produced from the process can be blended with the virtually distilled water coming from the thermal processes, thereby not requiring additional staged treatment within the SWRO plant. Further, operation of the HVAC system within the SWRO plant can be aided by using the chilled water stream from the AD plant. The hybrid concept of electricity generation, MED and SWRO has been proven to be effective at saving operational energy and cost. With the addition of AD, the hybrid efficiency is again increased.

In many arid regions, there is some seasonality in the demand for potable water and great fluctuation in electricity use [62]. With addition of an ASR component to the power/desalination campus, potable water can be stored to meet seasonal peak demands and for emergency use. Electric power cannot be readily stored to meet peak demands, but using excess power to desalt water during lower demand periods with placement into storage until it is needed improves overall system efficiency. The most efficient and cost-effective facilities are those that operate continuously at near their full capacity, so the ASR system allows this to occur. The overall power-desalination-storage campus concept allows the maximum economic efficiency to be achieved.

## 5. Conclusions

Use of geothermal energy to power electric generation and desalination is very desirable because of the generally renewable nature of the energy source. HDR geothermal reservoirs occur beneath a large percentage of the Earth's surface, but the heat harvesting well systems and surface infrastructure are expensive and require advanced technologies. To make HDR geothermal energy systems more economic, a second source of revenue is required. Therefore, the linking and integration of a number of thermal desalination processes with electric generation meets this need. Also, additional efficiencies are achieved when a SWRO facility is added along with an on-site ASR system.

At many electricity facilities using geothermal energy, waste steam is discharged to ambient causing significant loss of harvested latent heat that could be utilized to desalt seawater by using bled steam at low pressure to power the multi-effect distillation (MED) processes with a typical gain-to-output ratio (GOR) of 8. The exergy loss is roughly equivalent to a loss of

5–7% of electric generation capacity with an ambient steam discharge temperature of less than 75˚C.

The concept of a geothermal-powered electric-desalination-storage "campus" facility has the potential to provide a fully renewable system that has an extremely high efficiency. This concept could make HDR geothermal energy development projects become very competitive with conventional energy systems with resulting reductions in greenhouse gas emissions. Also, the use of ASR would mitigate the imbalances between electric demand and generation capacity, balance potable water demand and treatment capacity of a desalination plant(s), and reduce in maintenance down time with regard to electricity and water treatment.

## Acknowledgments

Research funding was provided by the Water Desalination and Reuse Center and discretionary faculty funding provided by the King Abdullah University of Science and Technology. The authors thank Drs Gary Amy and Noreddine Ghaffour for helpful reviews of the manuscript before submittal.

## References

[1] R. Dipippo, Geothermal Power Plants: Principle, Application and Case Study, Elsevier Science, UK, Oxford, 2005.
[2] R. Bandoro Swandaru, Thermodynamic Analysis of Preliminary Design of Power Plant Unit 1, West Java, Indonesia, The United Nations University Geothermal Training Programme Report 7, Reykjavik, Iceland, 2006, pp. 83–119.
[3] C. Axelsson, Reservoir engineering studies of small low-temperature hydrothermal systems in Iceland, Proc. 16th Workshop on Geothermal Reservoir Engineering, Stanford, CA, 23–25, January, 1991.
[4] A. Gunnarsson, B. Steingrimsson, E. Gunnlaugsson, J. Magnusson, R. Maack, R. Nesjavllir, Geothermal co-generation power plant, Geothermics 21 (1992) 559–583.
[5] I.A. Thain, 1985-1990 update on the existing and planned utilization for geothermal energy for electricity generation in New Zealand, Energy Sources 14 (1992) 205–216.
[6] M. Hanono, K. Kotanaka, T. Ohyama, A quarter century of geothermal power production at Matsukawa, Japan. Geothermal Resour. Council Bull. 22 (1993) 32–47.
[7] P.H.H. Siregar, Optimization of electrical power production process for the Sibayak geothermal field, Indonesia, Report 16, in: Geothermal training in Iceland, Iceland, UNU-GTP, 2004, pp. 349–375
[8] F.H. Harlow, W.E. Pracht, A theoretical study of geothermal energy extraction, J. Geophys. Res. 77 (1972) 7038–7048.
[9] M.C. Smith, A history of hot dry rock geothermal energy systems, J. Volcanol. Geotherm. Res. 15 (1983) 1–20.
[10] D.V. Duchane, Hot dry rock: A realistic energy option, Geotherm. Resour. Council Bull. 19(3) (1990) 83–88.
[11] R. Dipippo, Geothermal Power Plants: Principles, Applications, Case Studies and Environmental Impact, second ed., Butter-Heinemann, London, 2007.
[12] B.A. Goldstein, A.J. Hill, A. Long, A.R. Budd, F. Holgate, M. Malavazos, Hot dry rock energy plays in Australia, Proc. 34rth Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, 9–11 February 2009.
[13] M.C. Smith, The Future of Hot Dry Rock Geothermal Energy Systems. Am. Soc. Mech. Eng., Publication 79-PVP-35; 1979, 12.
[14] Z.J. Wan, Y.S. Zhao, J.R. Kang, Forecast and evaluation of hot dry rock geothermal resource in China, Renewable Energy 30(12) (2005) 1831–1846.
[15] D.W. Brown, D.V. Duchane, G. Heiken, V.T. Hriscu, Mining the Earth's Heat: Hot Dry Rock Geothermal Energy, Springer, New York, NY, 2012.
[16] Z. Feng, Y. Zhao, A. Zhou, N. Zhang, Development program of hot dry rock geothermal resource in the Yangbajing Basin of China, Renewable Energy 39 (2012) 490–495.
[17] R.P.I. Harrison Doherty Coulson, HDR cost modeling, in: R. Baria (Ed.), Hot Dry Rock Geothermal Energy, Redruth, Cornwall, UK, Proc. Camborne School of Mines international Hot Dry Rock Conference, 27–30 June 1989, Robertson Scientific Publications, London, 1989, pp. 245–261.
[18] Geothermal Energy Association (GEA), Factors Affecting Costs of Geothermal Power Development, August, 2005. Available from: <http://www.geo-energy.org> (accessed September 26, 2013).
[19] L. Awerbach, A.N. Rogers, W.A. Fernelius, Geothermal desalination, Alghero: Proc. International Symposium on Fresh Water from the Sea, 16–20 May 1976.
[20] C.A. Swanberg, P. Morgan, C.H. Stoyer, J.C. Witcher, An Appraisel Study of the Geothermal Resources of Arizona and Adjacent Areas in New Mexico and Utah and Their Value for Desalination and Other Uses, Las Cruces, New Mexico, New Mexico Energy Institute Report No. NMEI-6-1, 1977.
[21] A. Ophir, Desalination plant using low grade geothermal heat, Desalination 40 (1982) 125–132.
[22] L. Chaturvedi, C.G. Keyes, C.A. Swanberg, Y.P. Gupta, Use of Geothermal Energy for Desalination in New Mexico, Las Cruces, New Mexico, New Mexico Energy Institute Report No. NMEI-42, 1979.
[23] P.B. Chandler, Coastal zone geothermal desalination, Honolulu, Hawaii: Proc. 10th Annual Conference and Trade Fair of the Water Supply Improvement Association, 1982.
[24] S. Kalogirou, Seawater desalination using renewable energy sources, Prog. Energy Combust. Sci. 31 (2005) 242–281.
[25] G.Hiriart, Geothermal energy for desalination of seawater, in: Olso, Norway, 33rd International Geological Congress Abstracts 33, 2008.
[26] C. Karytsas, Low—Enthalpy geothermal seawater desalination plants, Bull. Geotherm. Resour. Council 4 (1998) 111–115.

[27] F. Benjemaa, I. Houcine, M.H. Chahbani, Potential of renewable energy development for water desalination in Tunisia, Renewable Energy 18(3) (1999) 331–347.
[28] K. Bourouni, R. Martin, L. Tadrist, Analysis of heat transfer and evaporation in geothermal desalination units, Desalination 122 (1999) 301–313.
[29] K. Bourouni, R. Martin, L. Tadrist, M.T. Chaibi, Heat transfer and evaporation in geothermal desalination units, Appl. Energy 64 (1999) 129–147.
[30] A.M.I. Mohamed, N.A.S. El-Minshawy, Humidification–dehumidification desalination system driven by geothermal energy, Desalination 249 (2009) 602–608.
[31] A. Ko, D.B. Guy, S.V. Cabibbo, Geothermal desalination and power generation. Trans. Geotherm. Energy Council 1979 3341–3344.
[32] M. Goosen, H. Mahmoudi, N. Ghaffour, Desalination using geothermal energy, Energies 3(8) (2010) 1423–1442.
[33] T.M. Missimer, Y.-D. Kim, R. Rachman, K.C. Ng, Sustainable renewable energy seawater desalination using combined-cycle solar and geothermal heat sources, Desalin. Water Treat. 51 (2013) 1161–1170.
[34] R. Sarbatly, C.K. Chiam, Evaluation of geothermal energy in desalination by vacuum membrane distillation, Appl. Energy 112 (2013) 737–746.
[35] T.M. Missimer, K.C. Ng, K. Thu, Y. Kim, Systems and Methods for Integrated Geothermal Electricity Generation and Water Desalination, United States Provisional Patent Application 6197081 (2014).
[36] B. Lindahl, Industrial and other applications of geothermal energy, except power production and district heating, in: H.C.H. Armstead (Ed.), UNESCO, Geothermal Energy, Earth Science 12 (1973) 135–148.
[37] B. Lindahl, Review of industrial applications of geothermal energy and future considerations, Geothermics 21 (1992) 617–622.
[38] Halliburton Inc. Available from: <www.halliburton.com/public/solutions/contents/shale/..../H063771.pdf> (accessed October 2, 2013).
[39] A.J. Nugroho, Optimization of electrical power production from high temperature geothermal fields with respect to silica scaling problems. Reykjavik, Iceland: MSc Thesis, Faculty of Mechanical and Industrial Engineering, School of Engineering and Natural Sciences, University of Iceland, 2011.
[40] O.A. Mamed, Overview of hybrid systems—Current status and future prospects, Desalination 186 (2005) 2699–2709.
[41] O.A. Hamed, H.A. Alwashmi, H.A. Alotaibi, Thermoeconomic analysis of a power/water cogeneration plant, Energy 31 (2006) 2699–2709.
[42] M. Elimelech, W.A. Phillip, The future of seawater desalination: Energy, technology, and the environment, Science 333 (2011) 712–717.
[43] I. Stober, K. Bucher, Geothermal Energy: From Theoretical Models to Exploration and Development, Springer, Berlin.
[44] A. Chakraborty, B.B. Saha, K.C. Ng, S. Koyama, K. Srinivasan, Theoretical insight of physical adsorption for single component adsorption-adsorbate system: I, Langmuir 25(4) (2009) 2204–2211.
[45] A. Chakraborty, B.B. Saha, K.C. Ng, S. Koyama, K. Srinivasan, Theoretical insight of physical adsorption for single component adsorption-adsorbate system: II, Langmuir 25(13) (2009) 7359–7367.
[46] K.C. Ng, K. Thu, Y. Hideharu, B.B. Saha, A. Chakraborty, T.Y. Al-Ghasham, Apparatus and Method for Improved Desalination, Patent PCT/SG2009/000223, 2010.
[47] K. Thu, Y.-D. Kim, G. Amy, W.G. Chun, K.C. Ng, A hybrid multi-effect distillation and adsorption cycle, Appl. Energy 104 (2013) 810–821.
[48] K. Thu, Y.-D. Kim, G. Amy, W.G. Chun, K.C. Ng, A synergetic hybridization of adsorption cycle with the multi-effect distillation (MED), Appl. Therm. Eng. 62 (1) (2014) 245–255.
[49] A. El Amali, S. Bouguecha, M. Maalej, Experimental study of air gap and direct contact membrane distillation configurations: Application to geothermal and seawater desalination, Desalination 168 (2004) 357–358.
[50] S. Bouguecha, M. Dhahbi, Fluidised bed crystalliser and air gap membrane distillation as a solution to geothermal water desalination, Desalination 152 (2003) 237–244.
[51] S. Alobaidani, E. Curcio, F. Macedonio, G.D. Diprofio, H. Alhinai, E. Drioli, Potential of membrane distillation in seawater desalination: Thermal efficiency, sensitivity study and cost estimation, J. Membr. Sci. 323 (2008) 85–98.
[52] L. Francis, N. Ghaffour, A. Alsaadi, G. Amy, Material gap membrane distillation: A new design for water vapor flux enhancement, J. Membr. Sci. 448 (2013) 240–247.
[53] A. Alsaadi, N. Ghaffour, J.D. Li, S. Gray, L. Francis, H. Maab, G.L. Amy, Modeling of air-gap membrane distillation process: A theoretical and experimental study, J. Membr. Sci. 445 (2013) 53–65.
[54] A. Chakraborty, K.C. Leong, K. Thu, B.B. Saha, K.C. Ng, Theoretical insight of adsorption cooling, Appl. Phys. Lett. 98(22) (2011) 221910.
[55] A. Chakraborty, K. Thu, K.C. Ng Advanced adsorption cooling cum desalination cycle: A thermodynamic framework, ASME 2011 Int. Mech. Eng. Congr. Exposition 4 (2011) 605–610.
[56] K.C. Ng, K. Thu, B.B. Saha, A. Chakraborty, Study on a waste heat-driven adsorption cooling cum desalination cycle, Int. J. Refrig. 35 (2012) 685–693.
[57] J.E. Miller, Review of Water Resources and Desalination Technologies, Sandia National Laboratories, Report 2003–0800.
[58] N. Ghaffour, T.M. Missimer, G.L. Amy, Technical review and evaluation of the economics of water desalination: Current and future challenges for better water supply sustainability, Desalination 309 (2013) 197–207.
[59] R.R. Wright, T.M. Missimer, Power optimization in membrane plants using aquifer storage and recovery, in: San Diego, CA: Proc. IDA World Congress on Desalination and Water Reuse, 1999, pp. 361–376.
[60] E. Al-Katheeri, S.P. Agashichev, Feasibility of the concept of hybridization of existing co-generative plant with reverse osmosis and aquifer storage, Desalination 222 (2008) 87–95.
[61] R.G. Maliva, T.M. Missimer, Aquifer Storage and Recovery and Managed Aquifer Recharge Using Wells: Planning, Hydrogeology, Design, and Operation. Methods in water resources evaluation series no. 2, Sugar Land, Texas, Schlumberger.
[62] T.M. Missimer, S. Sinha, N. Ghaffour, Strategic aquifer storage and recovery of desalinated water to achieve water security in the GCC/MENA region, Int. J. Environ. Sustain. 1(3) (2012) 89–100.