Energies **2010**, *3*, 1423-1442; doi:10.3390/en3081423

OPEN ACCESS

energies

ISSN 1996-1073

www.mdpi.com/journal/energies

Review

Water Desalination Using Geothermal Energy

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Received: 22 June 2010 / Accepted: 2 August 2010 / Published: 3 August 2010

Abstract: The paper provides a critical overview of water desalination using geothermal resources. Specific case studies are presented, as well as an assessment of environmental risks and market potential and barriers to growth. The availability and suitability of low and high temperature geothermal energy in comparison to other renewable energy resources for desalination is also discussed. Analysis will show, for example, that the use of geothermal energy for thermal desalination can be justified only in the presence of cheap geothermal reservoirs or in decentralized applications focusing on small-scale water supplies in coastal regions, provided that society is able and willing to pay for desalting.

Keywords: water desalination; geothermal energy; renewable energy; case studies; environmental risks; market potentials; barriers to growth

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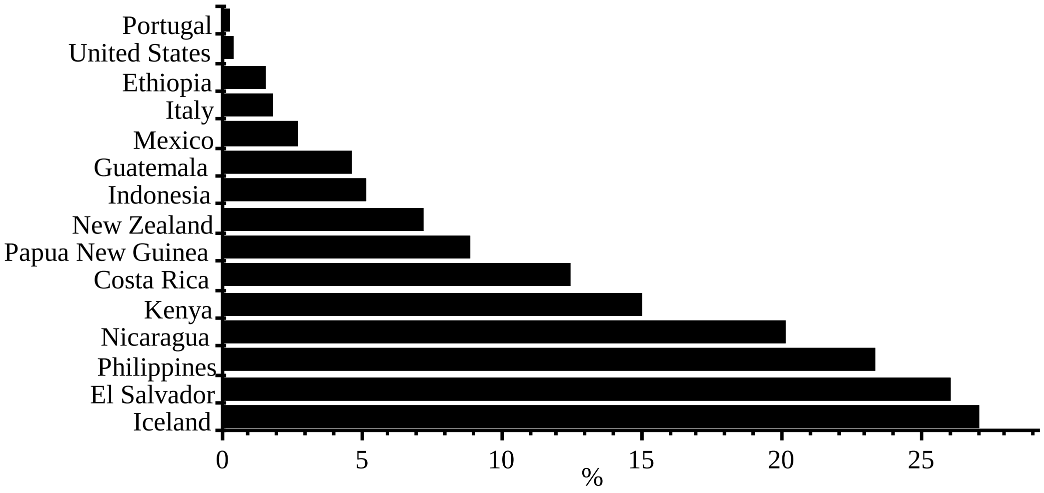
1. Introduction

The economic and industrial potential of geothermal energy as well as its environmental risks have been pointed out in several studies [1–7]. Lund [4] noted that recorded accounts show uses of geothermal water for bathing, cooking and space heating by Romans, Japanese, Turks, Icelanders, Central Europeans and the Maori of New Zealand. The first use of geothermal energy for electric power production occurred in Italy a century ago with the commissioning of a commercial power plant

(250 kWe). This was followed by similar plants at Wairakei in New Zealand in 1958; an experimental plant at Pathe, Mexico in 1959; the first commercial plant at The Geysers in the United States in 1960, and at Matsukawa, Japan, in 1966 [5]. All of these early plants used steam obtained directly from the earth (*i.e.* dry steam fields), except for New Zealand, which was the first to use flashed or separated steam for running the turbines. An assessment of geothermal resources in the United States has also been reported by White and Williams [8]. The former USSR produced power (680 kWe) from the first true binary power plant, using 81 ℃ water at Paratunka on the Kamchatka peninsula, the lowest temperature at that time. Iceland first produced power at Namafjall in northern Iceland, from a 3 MWe non-condensing turbine. These were followed by plants in El Salvador, China, Indonesia, Kenya, Turkey, Philippines, Portugal (Azores), Greece and Nicaragua in the 1970s and 80s. Later plants were installed in Thailand, Argentina, Taiwan, Australia, Costa Rica, Austria, Guatemala, Ethiopia, with the latest installations in Germany and Papua New Guinea [5]. Bouchekima [9] reported on the use of brackish underground geothermal water to feed a solar still installed in the south of Algeria. Iceland is widely considered as the most successful state in the geothermal community. The country of just over 300,000 people is fully (*i.e.* 100%) powered by renewable forms of energy in terms of electricity production (Figure 1), ranking the highest in the 15 top countries that generate electricity from geothermal resources.

Figure 1. Share of total electricity generation from geothermal resources in the top 15 countries [10].



Geothermal energy comes from the natural generation of heat, primarily due to magma, as well as the decay of the naturally occurring radioactive isotopes of uranium, thorium and potassium in the earth. The total thermal energy to a depth of 10 km is estimated at 1.3×10^{27} J, equivalent to burning 3.0×10^{17} barrels of oil. Wright [11] has reported that worldwide energy utilization is equal to about 100 million barrels of oil per day. Based on this he has estimated that the Earth’s high temperature hydrothermal reservoir to a depth of 10 kilometers could theoretically supply all of mankind’s power needs for several million years (Figure 2). On average, the temperature of the Earth increases about 30 ℃/km of depth. Thus, the temperature at 10 km would be over 300 ℃. However, most geothermal exploration occurs where the gradient is higher, and thus where drilling can be shallower and less costly.

Geothermal resources may therefore be classified by type of rock formation/form of water and temperature, ranging from 20 °C to over 300 °C [4]. Resources above 150 °C are normally used for electric power generation, although power has recently been generated at Chena Hot Springs Resort in Alaska using a 74 °C geothermal resource [12]. Resources below 150 °C are typically used in direct-use projects for heating and cooling.

Fridleifsson *et al.* [13] has reported that electricity is produced by geothermal means in 24 countries. Furthermore, direct application of geothermal energy for heating and bathing has been reported by 72 countries. By the end of 2004, the worldwide use of geothermal energy was 57 TWh/yr of electricity and 76 TWh/yr for direct use. Six developing countries are among the top fifteen states reporting direct use with China on the top of the list. Fridleifsson *et al.* [13] goes on to argue that it is considered possible to increase the installed world geothermal electricity capacity from the current 10 GW to 70 GW with present technology, and to 140 GW with enhanced technology.

The coupling of renewable energies such as wind, solar and geothermal with desalination systems holds great promise for increasing water supplies in water scarce regions [2,14,15]. It can be argued that an effective integration of these technologies would allow countries to address water shortage problems with a domestic energy source that does not produce air pollution or contribute to the global problem of climate change. Furthermore this approach will help to bypass the problems of rising fuel prices and decreasing fossil fuel supplies. Desalination plants, for example, may be run with geothermal energy being employed directly to heat the saline or brackish water in multiple effect distillation units and/or it could be used indirectly to generate electricity for operating reverse osmosis units [16]. Ophir [17] presented an economic study of desalination powered by a geothermal resource of 110–130 °C. Another technical and economic study was conducted by Karytsas [18] to analyze the feasibility of using geothermal resources between 75 and 90 °C to power a multiple effect boiling system (MEB). Bourouni *et al.* [19–21] reported on installations using humidification dehumidification processes in the form of evaporators and condensers made of polypropylene and operated at a temperature between 60 and 90 °C. Furthermore, with the recent progress in membrane distillation technology, the utilization of direct geothermal brine with temperature up to 60 °C has shown promise [22].

The aim of this paper is to provide a critical overview of seawater and brackish water desalination using geothermal resources. Specific case studies are presented as well as an assessment of environmental risks and market potentials. The availability and suitability of geothermal energy in comparison to other renewable energy resources for desalination are also discussed.

2. Desalination Using Renewable Energies

The combination of a renewable energy, such as wind, solar and geothermal, with desalination systems holds immense promise for improving potable water supplies in arid regions [2,14,23,24]. It can be argued that an efficient amalgamation of these technologies will allow nations to deal with water shortage problems with a domestic energy source that does not produce air pollution or contribute to the global crisis of climate change. Repetitive! Furthermore, while fuel prices are rising and fossil fuel supplies are decreasing, the fiscal outlay for desalination and renewable energy systems is steadily decreasing. The latter is due in part to a variety of possible arrangements that can be envisaged between renewable power supplies and desalination technologies [25,26].

One of the more successful solar desalination devices is the multiple-effect still [27]. Latent heat of condensation is recovered, in two or more stages (generally referred to as multi-effects), so as to increase production of distillate water and improve system efficiency. A key feature in improving overall thermal efficiency is the need to gain a better understanding of the thermodynamics behind the multiple use of the latent heat of condensation within a multi-effect humidification-dehumidification solar still [27]. In addition, while a system may be technically very efficient it may not be economic (*i.e.,* the cost of water production may be too high) [28]. Therefore, both efficiency and economics need to be considered when choosing a desalination system. It can be further argued that desalination units powered by renewable energy systems are uniquely suited to provide water and electricity in remote areas where water and electricity infrastructures are currently lacking.

Considering that the energy requirements for desalination continues to be a highly influential factor in system costs, the integration of renewable energy systems with desalination seems to be a natural and strategic coupling of technologies [29]. As an example of the potential, the southern part of the country of Algeria consists almost entirely (*i.e.* 90%) of the great expanse of the Sahara Desert. This district has fresh water shortages but also has plenty of solar energy [9], wind energy [23,24] and important geothermal reservoirs [2,30]. The amalgamation of renewable resources with desalination and water purification is thus very attractive for this district (Table 1). This will be discussed in more detail in the Case Study section.

Table 1. Renewable energy sources (RES) desalination combinations [2].

Renewable energy sources technology	**Feed water salinity**	**Desalting technologies**				
		Multiple effect boiling (MEB)	**Multi-stage flash (MSF)**	**Reverse osmosis (RO)**	**Electrodialysis (ED)**	**Compression (MVC)**
Solar thermal	Seawater	✓	✓			
Photovoltaic	Seawater			✓		
	Brackish water			✓	✓	
Wind	Seawater			✓		✓
	Brackish water			✓		
Geothermal	Seawater	✓				

The two most successful commercial water desalination techniques involve thermal and membrane separation methods [2,15,31]. The first method involves heating saline or brackish water to produce water vapor and then condensing the vapor to give pure water. The second method is based on size exclusion where the smaller water molecules can pass through a semi permeable membrane but the larger salt molecules cannot. Thermal separation processes include multi stage flash (MSF), multi effect evaporation (MEE)/multi effect distillation (MED), vapor compression (VC) and solar desalination. Membrane separation processes include reverses osmosis (RO) and electro-dialysis (ED).

Reverses osmosis desalination will become increasingly more competitive with thermal desalination processes in the next decade.

3. Geothermal Energy and Desalination

When using geothermal energy to power systems such as desalination plants we avoid the need for thermal storage. In addition, the energy output of this supply is generally stable compared to other renewable resources such as solar and wind power [31]. Kalogirou [16] has shown that the ground temperature below a certain depth remains relatively constant throughout the year. Popiel *et al.* [32] reported that one can distinguish three ground zones; surface, shallow and deep, with geothermal energy sources being classified in terms of their measured temperatures as low (<100 °C), medium (100–150 °C) and high temperature (>150 °C), respectively.

Geothermal wells deeper than 100 m can reasonably be used to power desalination plants [16]. The utilization of geothermal power directly as a stream power in thermal desalination plants can also be envisaged. Furthermore, with the recent progress on membranes distillation technology, the utilization of direct geothermal brine with temperature up to 60 °C has become a promising solution [22].

Improved heat exploitation technologies, which are still at the trial stage, have huge potential for primary energy recovery of the Earth’s stored thermal energy [11,16]. Direct use of geothermal energy for heating is also commercially competitive with conventional energy sources. An exponential increase is foreseen in the geothermal heat pump sector, for heating and/or cooling. There is an environmental advantage in that geothermal heat pumps driven by fossil fuelled electricity reduce the CO_2 emission by at least 50% compared with fossil fuel fired boilers. This will be discussed in more detail in the section on *Environmental Considerations*. Furthermore, we support Bertani’s [33] view that renewable energy sources can contribute significantly to the mitigation of climate change by reducing the use of fossil fuels.

Geothermal energy is accessible day and night every day of the year and can thus serve as an add-on to energy sources which are only available intermittently. An MIT-study indicates a potential of more than 100 GW for USA and 35 GW for Germany [34,35]. It is likely that up to 8% of the total world electricity may be produced with geothermal resources, serving 17% of the world population [36]. Thirty nine countries, situated by and large in Africa, Central/ South America, and the Pacific, can potentially obtain 100% of their electricity from geothermal resources [37].

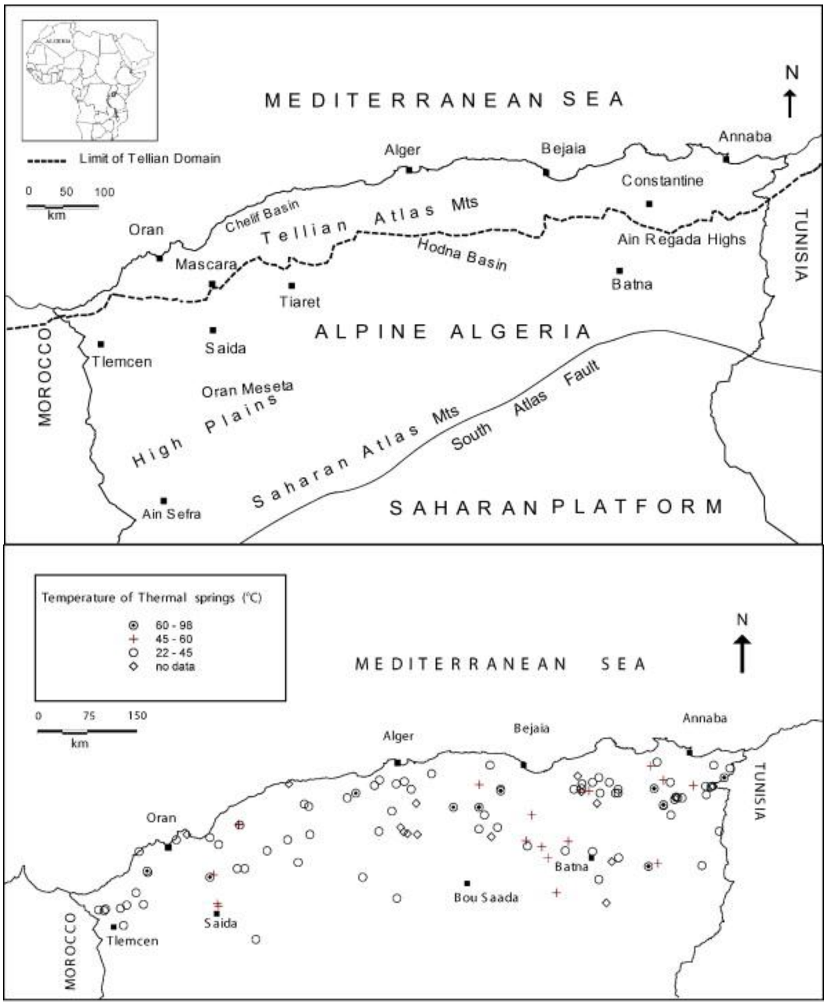
4. Case Studies

4.1. Capacity Building Strategies for Desalination Using Renewable Energies in Algeria and the Proposed Seawater Greenhouse System

Algeria is an oil and gas producer; hence decision makers there believed that encouraging use of renewable energies can affect the country's oil exports [24,38]. The country is also Africa’s second-largest nation and the eleventh in the World in terms of land area, being bordered in the north by 1,200 km of Mediterranean coastline. Among the major challenges facing the region are limited water and energy resources? as well as risk management of the environment [24,39]. Mahmoudi *et al.* [2] has argued that due to the world economic crisis and the decreasing oil and gas reserves, decision makers in arid countries such as Algeria, need to review their policies regarding the promotion of renewable energies.

Geothermal energy represents one of the most significant sources of renewable energies in the case study area. This can be divided into two major structural units by the South Atlas Fault (Figure 2a); with Alpine Algeria in the north and the Saharan Platform in the south. The northern region formed by the Tellian Atlas, the High Plains and the Saharan Atlas. This part is characterized by an irregular distribution of its geothermal reservoirs (Figure 2b). The Tellian nappes, constitute the main geothermal reservoirs. Hot ground water is generally at neutral pH, total dissolved salts (TDS) are up to 10 g/L and can reach a temperature in the range of 22 ℃ to 98 ℃ [30,40]. The southern region formed by the Algeria northern Sahara is characterized by a geothermal aquifer which is commonly named the 'Albian reservoir'. The basin extends to Libya and Tunisia in the East and covers a total surface of 1 million km^2. This part of Algeria is estimated at 700,000 km^2 and contains approximately 40 thousand billion m^3 of brackish groundwater water. The depth of the reservoir varies between 200 m in the west to more than 1,000 m in the east. Deeper wells can provide water at 50 to 60 ℃ temperature, 100 to 400 L/s flow rate and average TDS (total dissolved solids) of 2g/L.

Figure 2. Top (a): Geological units of Northern Algeria [2,38]; Bottom (b): Main thermal springs in northern Algeria [2,38].



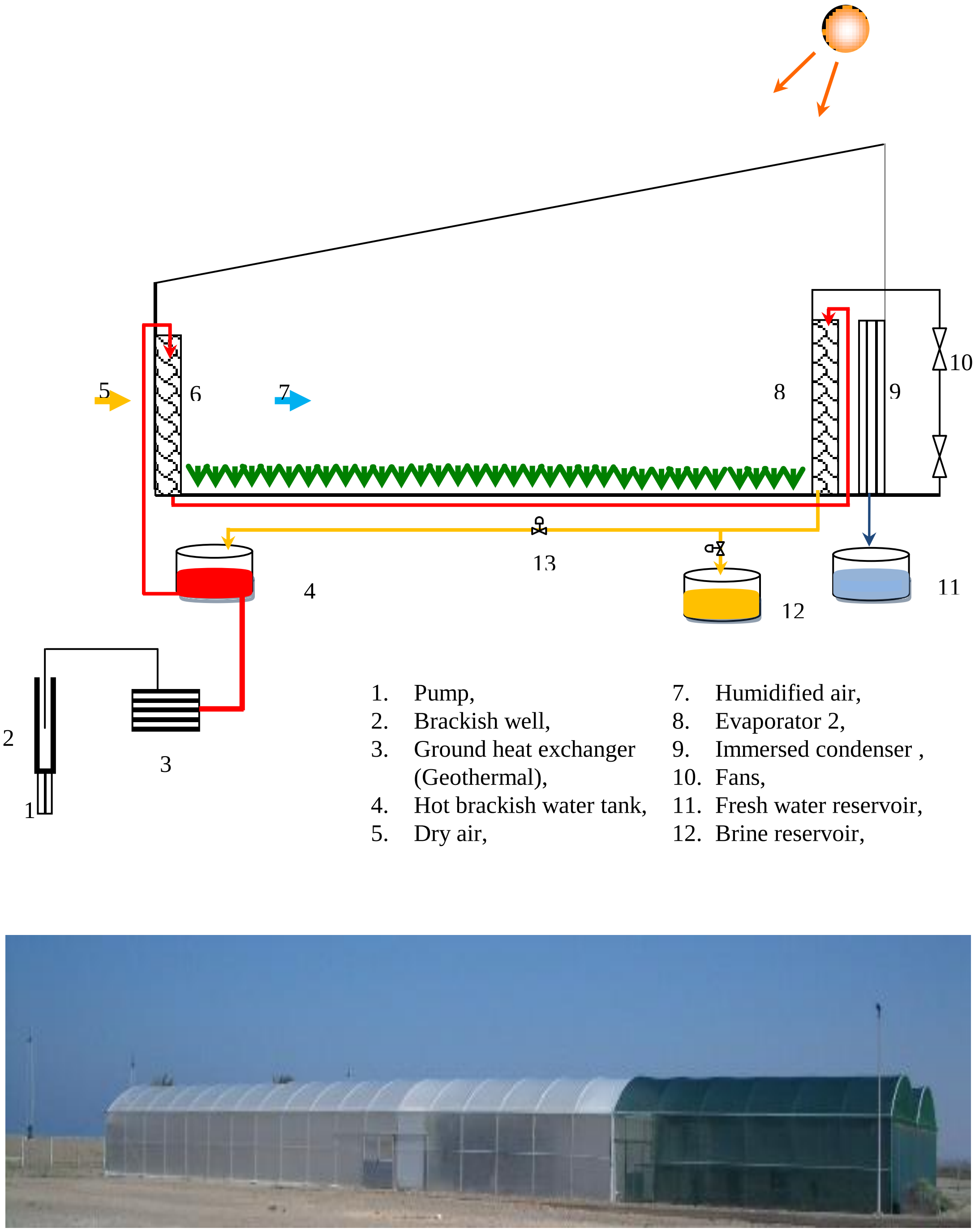
In 1988, an ambitious program was established with the aim to expand the utilization of geothermal heated greenhouses in regions affected by frost; sites in eastern and southern region of the state. Unfortunately, this program was hampered by security concerns [30]. In the last few decades, much effort has also been expended to exploit the numerous thermal springs of the North and the hot water wells of the Saharan reservoir (Figure 2b). More than 900 MWt is expected to be produced in the future [30,40].

Mahmoudi *et al.*, [2] in a recent report proposed the application of geothermal sources to power a brackish water greenhouse desalination system for the development of arid and relatively cold regions, using Algeria as a case study (Figure 3a). He noted that countries which have abundant sea/brackish water resources and good geothermal conditions are ideal candidates for producing fresh water from sea/brackish water. The establishment of human habitats in these arid areas strongly depends on availability of fresh water.

Geothermal resources can both be used to heat the greenhouses and to provide fresh water needed for irrigation of the crops cultivated inside the greenhouses. University of Queensland’s Geothermal Energy Center’s director Hal Gurgenci was quoted as saying that geothermal-powered desalination systems could be a boon for small towns facing water shortages [41]. He went on to state that this is a clever combination where desalination is coupled with an agricultural function which is both cost-efficient and environmentally-friendly. Gurgenci said that while some of the geothermal resources may not be hot enough for power generation, they would be a perfect fit for thermal desalination of underground brackish aquifers. Studies indicate that for plants in the range of one to 100 megalitres (a megalitre is one million liters) per day, thermal desalination technologies are more suitable than reverse osmosis especially if there is a cheap and abundant supply of heat. Geothermal heat can be used to heat and to humidify a greenhouse and produce fresh water at the same time.

The brackish water is pumped and filtered from a well and sent into a ground heat exchanger where it absorbs heat from a geothermal fluid. This heat exchanger can be built of polyethylene to conserve costs. The heated brackish water is then fed in a cascade to the first evaporator then to the second evaporator. The brine can be circulated in the circuit several times until its concentration increases over an acceptable dissolved salt concentration. The concentrated brine is finally collected in a tank, where it is stored for later treatment or processing or reinjection. The evaporator is the entire front wall of the greenhouse structure. It consists of a cardboard honeycomb lattice and faces the prevailing wind. Hot brackish water trickles down over this lattice, heating and humidifying the ambient cooler air passing through into the planting area and contributing to the heating of the greenhouse. Fans draw the air through the greenhouse. Air passes through a second evaporator and is further humidified to saturation point. Air leaving the evaporator is nearly saturated and passes over the passive cooling system with a condenser (IC) immersed in a water basin. The fresh water condensing from the humid air is piped for irrigation or other purposes. This design can be scaled up to provide 10–20 kL/day while also helping greenhouse plant growing.

Figure 3. Top (a): Process schematic for Brackish Water Greenhouse coupled to geothermal system [2]. Greenhouse cover is normally plastic sheeting and the feed water to the pump is either brackish groundwater or sea water from a beach well; Bottom (b): The Seawater Greenhouse at Al-Hail, Muscat, Oman [14].



The innovative idea of a seawater greenhouse was originally developed by Seawater Greenhouse Ltd in 1991 [31,42,43]. The first pilot was built and tested in the Canary Island of Tenerife in 1992, once known as the 'Garden of the Gods', but now arid and gravely damaged by excessive abstraction of ground water [42]. The early results showed were promising and demonstrated the possibility to develop the technology in other arid regions. A modified and improved novel seawater greenhouse was constructed on Al-Aryam Island, Abu Dhabi, United Arab Emirates in 2000 [44]. For both pilot studies the production of crops was excellent, and fresh water was successfully produced for the greenhouse irrigation proposes. In 2004 Seawater Greenhouse Ltd in collaboration with Sultan Qaboos University built a new pilot Seawater Greenhouse near Muscat, Oman (Figure. 3b) [14]. The aim of the project was to demonstrate the technology to local farmers and organizations in the Arabian Gulf.

4.2. Geothermal Energy in Seawater Desalination in Milos Island Greece

Milos Island is located in the Aegean Volcanic Arc and is characterized by abundant geothermal resources [45]. Early geothermal exploration undertaken by the Institute of Geological and Mining Research of Greece indicated that the eastern part of the island and especially the plain of Zefyria was the region with the highest temperature gradients, hence most promising for high enthalpy geothermal potential. Later drilling exploration identified geothermal fluids of temperature 300–323 °C at depths 800–1,400 m below sea level. In contrast, Karytsas *et al.*, [45] found that the region of the island most promising for exploitation of shallow, low enthalpy (<100 °C) geothermal resources was the eastern half of the island. The deep geothermal fluids corresponded to boiled seawater of 80,000 ppm salinity. It was determined that the upper 2 km of the hot rocks below Zefyria could support a 260 MWe geothermal power plant.

The main objective of the Milos Island project reported by Karytsas *et al.*, [45] was to construct and operate a low enthalpy geothermal energy driven water desalination unit producing 80 m^3/h of drinking water and a 470 kWe power generator unit. The plant consisted of a dual system with the hot water from the deep geothermal wells being employed to run organic Rankine cycle (ORC) turbines for electricity generation and at the same time being used directly in a multiple effect boiler or distillation unit (MED) (see also MEB in Table 2). The working principle of the organic Rankine cycle (ORC) is the same as that of the Rankine cycle: the working fluid is pumped to a boiler where it is evaporated, passes through a turbine which generates the electricity and is finally re-condensed. Furthermore, multiple-effect distillation (MED) is basically a boiling process often used commercially for sea water desalination. It consists of multiple stages or "effects". In each stage the feed water is heated by steam in tubes. Some of the water evaporates (this is pure water), and this steam flows into the tubes of the next stage, heating and evaporating more water. Each stage essentially reuses the energy from the previous stage. The tubes can be submerged in the feed water, but more typically the colder salty feed water is sprayed on the top of a bank of horizontal hot tubes (containing the pure water vapor). The vapor inside the tubes then condenses and drips from tube to tube until it is collected at the bottom of the stage.

The only source of energy for the Milos Island project reported by Karytsas *et al.* [45] was geothermal heat. The unit is anticipated to be entirely self sufficient in thermal energy and to have the potential to become self sufficient in electricity as well. The local community would benefit from the production of desalinated water, which will be produced at a very low cost (*i.e.* 1.5 € per m^3) and from the utilization of a sustainable and environmentally friendly low enthalpy geothermal energy source. The geothermal power and desalination plant of the project consisted of the following components:

- Geothermal production wells: Production will be derived from the wells located closer to the sea, due to their high energy yield and the corresponding hot water transmission costs.

- Geothermal submersible pumps and inverters installed at the production wells.
- Piping network conveying the geothermal water to the main Plant.
- Organic Rankine Cycle (ORC) unit, transforming approximately 7% of geothermal energy to electricity designed to generate approximately 470 kWe.
- Multi Effect Distillation-Thermal Vapor Compression (MED-TVC) seawater desalination unit providing 75–80 m^3/h desalinated water.
- Main heat exchanger, transferring the energy from the hot geothermal water exiting the ORC unit to the MED-TVC desalination unit.
- Reinjection wells (RE I and II) located at the margin of the geothermal field, close to the coast, downstream and at lower elevation of the main Plant.
- Geothermal water transmission lines from main heat exchanger to reinjection wells.
- Seawater transmission lines conveying 1,000 m^3/h cooling seawater to the MED-TVC unit plus 200–575 m^3/h cooling water for the ORC unit.
- Desalinated water transmission line from plant to water tanks near adjacent town.
- Power substation for power provision or delivery to the local power net: 500 kWe.
- Main computer monitoring and control system for real time data logging and automation control.

4.3. Water Desalination with Geothermal Energy in Baja Peninsula Mexico

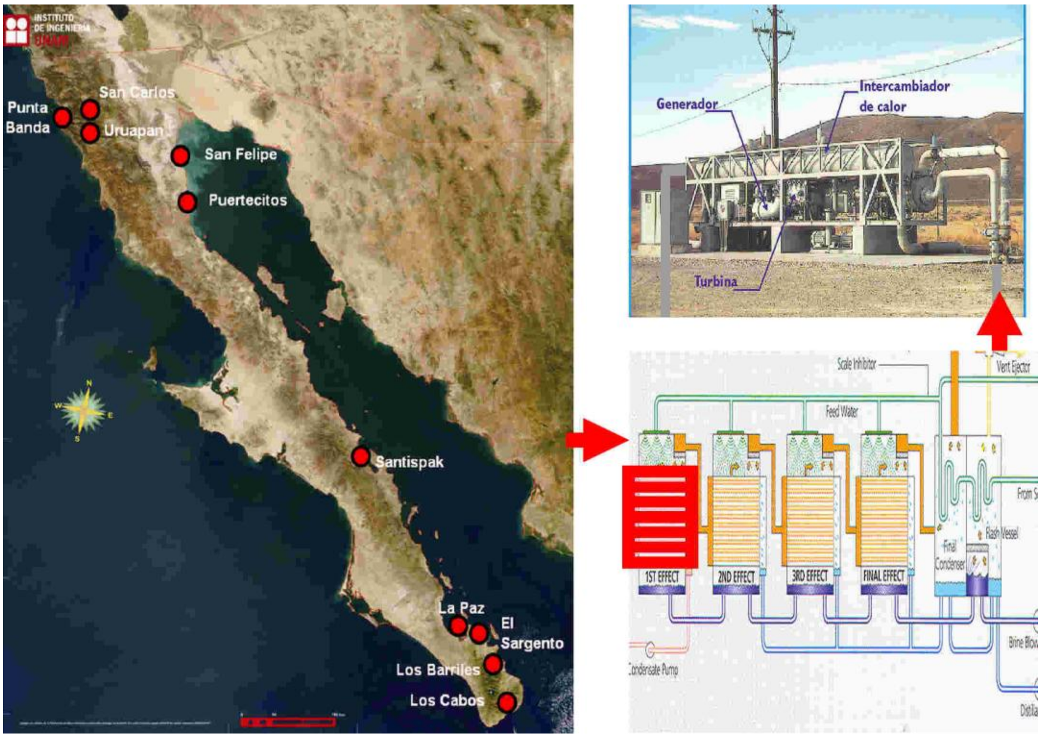
In Mexico, specifically in the arid region of Baja California, there is not only an abundance of traditional renewable resources like sun and wind but also hot springs, tidal currents and tidal amplitudes of over six meters in the upper part of the Gulf of California [46]. The National University of Mexico (UNAM) assessed the extent of these renewable resources and looked at ways to use them for desalinating sea water. The project had three specifics goals:

- To develop solutions to the scarcity of water in northwestern Mexico, considering the environment, costs and social impact of desalination.
- To form a solid group of engineers and researchers who would master the topics related to this project, and who would be able to transform science into applied solutions with a high degree of knowledge about renewable energies.
- At the end of this process, knowledge and expertise must be disseminated to society via courses, books, seminars, on-site training.

It was established that at only 50 m depth, very high temperatures could be obtained, sufficient for use in binary geothermal power plants to generate electricity for desalination. It was also found that the amount of electrical power that could be generated with tidal storage and from deep sea hydrothermal vents was of the order of several thousands of MW. Many locations with hot sea water were discovered (Figure 4), the best being at Los Cabos. As soon as the water table was reached, a temperature of 85 °C was found at 50 meters from the sea shore. Alcocer *et al.*, [46] went on to claim that having sea water at 90 °C available is a real advantage for thermal desalination; because this suggests temperatures around 150 °C as one drills deeper.

Using satellite imagery, hundreds of anomalous "hot spots", where large amounts of hot water reach the surface through geological fractures, were identified. The information was corroborated by measuring the water temperature directly in the field, and obtaining samples of the water to determine its isotopic composition and to better understand its origin. Although some of these hot springs and wells were on-shore, many were under-sea, close to the coast and at very shallow depths. The most important of these shallow, hot sea-water vents were near Puertecitos, Bahia Conception and Ensenada. In those cases field measurements and sampling required some diving. Each hot spring was different; some had high amounts of dissolved gases; others had lower salinity than the surrounding sea water; others had high sulfur content. This information was very valuable for the group in charge of designing the thermal desalinating equipment where the availability and the quality of the hot sea water were very important.

Figure 4. Left: Locations with hot sea water at 50 m depths in the Baja Peninsula in Mexico (red dots on map) with the Pacific Ocean on western side and the Gulf of California on the eastern side [46]; Upper right: Actual boiling or flashing effect (highlighted in red in previous schematic). (See also Table 1 and section 2 for further information about MED); Lower right: Schematic of multiple effects boiling/distillation (MED) (or flashing) thermal desalination system with first effect highlighted in red.



Hot water was used in a heat exchanger to heat clean seawater and then to decrease the pressure to produce instantaneous evaporation in a multistage set of chambers (Figure 4). The innovation introduced in the design was the use of hot sea-water to heat all the chambers, not just the first one as in a conventional Multi-Stage Flash (MSF) plant. The innovation can be considered as a combination of Multi-Effect Distillation (MED) and Multi-Stage Flash (MSF), called "Multi-Flash with Heaters" (MFWH). The principle behind both processes is the same; saline water is heated using hot geothermal water to produce pure water vapor which is then condensed on a cold surface to produce fresh water. Various types of commercial desalination equipment (*i.e.* MSF, MED, MFWH) have been developed in order to improve the technical/thermal efficiency of the process. Preliminary results indicated that for an initial temperature of 150 ℃, 4 m^3 of sea water were required to produce 1 m^3 of desalinated water. At an initial temperature of 80 ℃, 14 m^3 were required. For additional information on this topic see Rodrıguez *et al.* [25].

5. Environmental Considerations and Sustainability

Desalination of sea and brackish water requires large quantities of energy which normally results in a significant environmental impact if fossil fuels are used (e.g., CO_2 and SO_2 emissions, thermal pollution of seawater). The operating cost of different desalination techniques is also very closely linked to the price of energy. This makes the use of renewable energies associated with the growth of desalination technologies very attractive. We can argue that the ready availability of inexpensive oil and natural gas reserves in such areas of the world as the Arabian Gulf may reduce the need for using renewable energy for desalination. However, looking at this more closely we see that this is non-sustainable since fossil fuels are non-renewable, and with a continually growing population there is an ever increasing demand on the use of fossil fuels for desalination. Take Saudi Arabia as a specific example; in 2008 total petroleum (*i.e.* oil and gas) production was 10.8 million bbl/d with internal oil consumption at 2.4 million bbl/d (*i.e.* about 25%) [47]. Most of the internal consumption was used for electricity generation and water desalination. The population is expected to increase from 30 million in 2010 to approximately 100 million by 2050 [48]. It has been estimated that by then 50% of the fossil fuel production will be used internally in the country for seawater desalination in order to provide fresh water for the people. This will reduce the state's income, increase pollution and is clearly non-sustainable. There are also concerns about the resulting political instability which could arise due to these effects [49]. A possible solution to the environmental and sustainability problems is the increased use of renewable, including nuclear, energy sources for desalination [4,13,52].

Let us take a closer look at the environmental impacts that must be considered during utilization of geothermal resources as outlined by Rybach [50], Lund [4]; Kagel, *et al.*, [51] and Fridleifsson, *et al.* [13]. These include emission of harmful gases, noise pollution, water use and quality, land use, and impact on natural phenomena, as well as on wildlife and vegetation. The environmental advantages of renewable energy can be seen when comparing, for instance, a coal-fired power plant to a geothermal power plant; the former produces about 25 times as much carbon dioxide (CO_2) and sulfur dioxide (SO_2) emissions per MWh (*i.e.* 994 kg *vs.* up to 40 kg for CO_2, 4.71 kg *vs.* up to 0.16 kg for SO_2, respectively) [4,13] (Table 2). However, in a geothermal power plant hydrogen sulfide (H_2S) also needs to be routinely treated and converted to elemental sulfur since about 0.08 kg H_2S may be produced per MWh electricity generated. It can be argued that this is still much better than oil-fired power plants and natural gas fired plants which produce 814 kg and 550 kg of H_2S per MWh, respectively. The environmental advantages and sustainability of geothermal energy for electricity production in comparison with oil and coal fired power plants is therefore clearly demonstrated by a significant reduction in emissions of CO_2, SO_2, and H_2S as well as having a very low fresh water usage (Table 2).

Carbon dioxide (CO_2) emission from geothermal power plants in high-temperature fields is about 120 g/kWh (weighted average of 85% of the world power plant capacity). As explained above, there is an environmental advantage in that geothermal heat pumps driven by fossil fuelled electricity reduce the CO_2 emission by at least 50% compared with fossil fuel fired boilers. If the electricity that drives the geothermal heat pump can be produced from a renewable energy source like hydropower or geothermal energy, then the emission savings will increase up to 100%. The total CO_2 emission reduction potential of geothermal heat pumps has been estimated to be 1.2 billion tons per year or about 6% of the global emission [4,13].

Table 2 Comparison of CO_2, SO_2, H_2S emissions and fresh water usage from electricity generation (MWh) from different energy sources (adapted in part from Fridleifsson, *et al.* [13]).

Energy Source	**Coal**	**Oil (& Gas)**	**Geothermal**
CO_2 (Kg/MWh)	994	893 (599)	40–120
SO_2 (Kg/MWh)	4.71	−	0.16
H_2S (Kg/MWh)	−	814 (550)	0.08
Amount fresh water used (L/MWh)	1,370	1,170	20

Geothermal plants use about 20 liters of freshwater per MWh, while binary air-cooled plants use no fresh water, as compared to a coal plant that uses 1,370 liters per MWh [13]. The only change in the fluid during use is to cool it, and usually the fluid is returned to the same aquifer so it does not mix with the shallow groundwater. At The Geysers facility in northern California, for example, 42 million liters of treated wastewater are pumped daily for injection into the geothermal reservoir, reducing surface water pollution in the community and increasing the production of the geothermal field. A similar project supplies waste water from the Clear Lake area on the northeast side of the The Geysers. These projects have augmented the capacity of the field by over 100 MWe.

Geothermal power plants are designed to blend-in with the adjacent landscape, and can for instance be located near recreational areas with the least amount ground and visual impacts. They generally consist of small modular plants under 100 MWe as compared to coal or nuclear plants of around 1,000 MWe, with a geothermal facility normally using 400 square meters of land per GWh compared to a coal facility that uses almost ten times that much area per GWh and a wind farm that uses three times the area for the same power generation [4,13,51]. On the negative side, subsidence and induced seismicity (*i.e.* earthquakes) are two land use issues that must be considered when withdrawing fluids from the ground. These are usually mitigated by injecting the spent fluid back into the same reservoir. Problems with subsidence at the Wairakei geothermal field in New Zealand have been reported; however, this has been minimized by injection. Neither of these potential problems is associated with direct-use projects, as the fluid use is small. In addition, utilizing geothermal resources eliminates the mining, processing and transporting required for electricity generation from fossil fuel and nuclear resources.

With regards to impact on natural phenomena, wildlife and vegetation, geothermal plants are usually prohibited from being located near geysers, fumaroles (*i.e.* vents in the earth's crust from which volcanic gas escapes into the atmosphere) and hot springs, as the extraction of fluids to run the turbines, might affect these natural thermal phenomena. Most plants are located in areas with no natural surface discharges. If geothermal plants must be located near these natural phenomena, then the fluid extraction depth is planned from a different reservoir to prevent any impact. Any site considered for a geothermal power plant, must be reviewed and considered for the impact on wildlife and vegetation, and if significant, provide a mitigation plan. Direct use projects are usually small and thus have no significant impact on natural features. In summary, the use of geothermal energy is reliable, is renewable; has minimum air emission and offsets the high air emissions of fossil fuel fired plants; has minimum environmental impacts; is combustion free; and is a domestic fuel source. Economic aspects will now be discussed in the next section.

6. Market Potential, Barriers to Growth and Risk Management

The capital and operating costs for desalination plants have tended to decrease over the years due primary to improvements in technical efficiency [53]. At the same time that desalting costs have been decreasing, the price of obtaining and treating water from conventional sources has tended to increase because of the increased levels of treatment being required to meet more stringent water quality standards. This rise in cost for conventionally treated water also is the result of an increased demand for water, leading to the need to develop more expensive conventional supplies, since the readily accessible water sources have already been used up [26].

Many factors enter into the capital and operating costs for desalination: capacity and type of plants, plant location, feed water, labor, energy, financing, concentrate disposal, and plant reliability [54]. For example, the price of desalted seawater is about three to five times the cost of desalting brackish water from the same size plant, due primarily to the higher salt content of the former. In any state or district, the economics of using desalination is not just the number of dollars per cubic meter of fresh water produced, but the cost of desalted water versus the other alternatives (e.g., superior water management by reducing consumption and improving water transportation). In many arid areas, the cost of alternative sources of water (*i.e.* groundwater, lakes and rivers) is already very high and often above the cost of desalting. Any economic evaluation of the total cost of water delivered to a customer must include all the costs involved. This includes the costs for environmental protection (such as brine or concentrate disposal), and losses in the storage and distribution system.

Let us consider for a moment the barriers to growth (Table 3). Although we can recognize the potential of geothermal energy for seawater desalination, the process has not as yet been significantly developed at commercial level [53]. The main reason for this is that the existing technology cannot presently compete on produced water cost basis with conventional distillation and reverse osmosis technologies. On the other hand, it is also recognized that there is still important room to improve desalination systems based on geothermal energy. Technical design problems and high investment costs associated with indirect desalination still need to be overcome (e.g., converting thermal energy to electrical energy and using this in RO desalination). Thus the thermal distillation systems directly heated from geothermal sources will be the method of choice. The ongoing Milos low enthalpy geothermal power operation scheme [45] has confirmed that through innovation, sustainable utilization geothermal energy may be employed for electricity generation and seawater desalination in order to meet local water needs.

Table 3. Summary of market potential, barriers to growth and risk management of geothermal projects.

Market potential	• Thermal distillation system directly heated from ground well is currently preferred geothermal method due to fewer technical risks • In many arid areas, cost of groundwater, lakes and rivers is very high and often above cost of conventional desalting. This makes geothermal desalination commercially attractive • Geothermal projects benefited from increased prices of oil and gas and from public concern over dependence on these fossil fuel resources • Rise in cost for conventionally treated water due to increased demand for water, leading to need to develop more expensive conventional supplies, since readily accessible water sources have been used up
Barriers to growth	• Price of desalting seawater is 3 to 5 times cost of desalting brackish water from same size plant, due to higher salt content of former • Geothermal desalination process has not as yet been significantly developed at commercial level • Technical design problems and high investment costs associated with indirect desalination still need to be overcome • Electricity generation using geothermal power is only marginally profitable
Risk Management	• Manage budget over-runs, increases in interest rates, and delays. • Run profitability simulations in order to analyze varying scenarios before implementing project • Reserves must always be planned for in financing of project • Limit business risks by suitable structuring of contracts with partners in project (e.g., share risks with drilling companies, power-plant supplier, and civil-engineering companies) • Stakeholders bear drilling risk, (*i.e.* that drilling company may or may not find something, or not within time predicted, and thus within budget, or that well proves not to be usable for pumping thermal water) • Pass part of risk on to drilling company in contract • Geological risk (*i.e.* non-discovery) is main hazard; it can be reduced by reprocessing old seismic analyses and preparing new ones. • Non-geological risk covered by equity capital and/or comprehensive insurance that covers both thermal potential of wells, and also absorption capacity of injection wells • There must be a focus on legal and economic aspects from start of any large scale commercial project • Projects must keep standby pumps ready in order to deal with financial risks of a failure of delivery or injection pumps

7. Concluding Remarks

The cost for conventional desalination can be significant because of its intensive use of energy. However, the selection of a specific process should depend on a careful study of site conditions and the application at hand. Local circumstances will always play a significant role in determining the most appropriate process for an area. The best desalination system should be more than economically reasonable in the study stage. It should work when it is installed and continue to work and deliver suitable amounts of fresh water at the expected quantity, quality, and cost for the life of a project. Water scarcity is an increasing problem around the world and everybody agrees that seawater desalination can help to alleviate this situation. Among the energy sources suitable to drive desalination processes, geothermal energy is one of the most promising options, due to the ability to couple the availability of geothermal energy with water demand supply requirements in many world locations.

A geothermal desalination project carried out in Milos (Greece) has demonstrated the technical feasibility of this technology, through low enthalpy geothermal energy utilization in a multi-effect distillation unit (MED). In the future new technological developments in the design of absorption heat pumps, hybridization with other energy sources, cogeneration and recovery of salt, are expected to both improve the energy efficiency of the process and process economy. The expected result would be an enhanced MED technology with market possibilities and suitable for a variety of world locations. What may also prove a feasible option is the use of geothermal power from cheap reservoirs in coastal areas to desalt seawater in RO-plants.

Seawater desalination in itself is an expensive process, but the inclusion of geothermal energy sources and the adaptation of desalination technologies to renewable energy supplies can in some cases be a particularly less expensive and economic way of providing water. The use of geothermal energy for thermal desalination can be justified only in niches (e.g., in the presence of cheap geothermal reservoirs) or in decentralized applications focusing on small-scale water supply in coastal regions (e.g., village communities), provided the ability and willingness to pay for desalting is sufficiently large.

The World's water demands are rising considerably. Much research has been directed at addressing the challenges in using renewable energy to meet the power needs for desalination plants. Wind, solar and geothermal renewable technologies are rapidly emerging with the promise of economic and environmental viability for desalination. There is a need to accelerate the development of novel water production systems from renewable energies. These technologies will help to minimize environmental concerns.

In closing, our analysis has shown that there is great potential for the use of geothermal energy in many parts of the world. Geothermal sources could provide a viable source of energy to power both seawater and the brackish water desalination plants. Finally, it must be noted that part of the solution to the world’s water shortage is not only to produce more water, but also to do it in an environmentally sustainable way and to use less of it. This is one of the foremost challenges facing society.

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