

The Potential for Solar-Powered Desalination of Brackish Groundwater in Texas

394K – GIS in Water Resources – Dr. Maidment

By Jill Kjellsson

12/7/2012

Table of Contents

1	Introduction	2
2	Objective	2
3	Background	2
3.1	Water Issues in Texas	2
3.2	Desalination of Brackish Groundwater	2
3.3	Solar Potential in Texas	3
3.4	Solar-Powered Desalination	3
4	Data and Assumptions	4
5	Methodology	4
5.1	Spatial Variability of Brackish Groundwater Well Characteristics.....	4
5.2	Spatial Variability of Solar Radiation	5
5.3	Capacity of Solar-Powered Desalination	5
6	Results	6
7	Discussion and Conclusion.....	10
8	References.....	11

1 Introduction

As population and water demand in Texas increase, there is a need for new freshwater sources. Because brackish water is abundant, desalination of brackish water represents one possible alternative supply. However, desalination is an energy intensive treatment method which remains an inhibitor to its broader adoption. At the same time, concerns about carbon emissions and their effects on the climate favor the use of renewable energy over conventional fossil fuels. However, renewable energy technologies such as wind and solar are intermittent, which can present a challenge to grid operation if large-scale storage (such as batteries, pumped hydroelectric, or compressed air energy storage) is not available. One possible solution is to couple solar photovoltaic (PV) with desalination that can be operated intermittently, such that stored, treated water is a proxy for energy storage.

2 Objective

The objective of this project is to analyze the potential of co-locating desalination plants for inland brackish groundwater treatment and solar photovoltaic power generation. This project will explore the geographical component of such an analysis using GIS by comparing the locations of brackish groundwater resources, characterization of well parameters and solar radiation across Texas.

3 Background

3.1 Water Issues in Texas

The population of Texas is expected to increase 82% between 2010 and 2060 [11]. Meanwhile the water use is estimated to grow only 22% due to decreases in agricultural water use from efficiency improvements and municipal water use from conservation measures [11]. Municipal water demand is expected to increase from 4.9 million acre-feet in 2010 to 8.4 million acre-feet in 2060 while natural fresh water supplies are estimated to decrease 10% over this period [11]. Therefore, at the current rate of production and consumption, future supplies of water will not meet future demand unless alternative sources are tapped.

3.2 Desalination of Brackish Groundwater

Texas has an abundance of brackish groundwater, thought to be more than 2.7 billion acre-feet [5], which can be desalinated and used to meet public needs. Brackish groundwater is defined as water with a total dissolved solids (TDS) concentration of 1,000 – 10,000 mg/L. For comparison, seawater has a TDS concentration of 35,000 mg/L. The Texas Commission on Environmental Quality (TCEQ) has set a primary standard concentration for TDS of 500 mg/L and a secondary standard of 1,000 mg/L for public use [5].

Reverse osmosis (RO) and electrodialysis (ED) are the most common types of desalination systems. Reverse osmosis applies pressure to a solution on one side of a selective membrane to reverse the natural flow of solvent to the side with higher solute concentration. The solute remains while the pure solvent passes to the other side, thereby producing freshwater. Electrodialysis uses electromotive forces applied to electrodes that are adjacent to both sides of a membrane to

purposely move salt ions through the membrane leaving behind freshwater. ED is best applied to treatment of brackish-water with TDS up to 5,000 mg/L and is not economical for higher concentrations [1]. Both methods are used coupled with PV systems [1]. In Texas, RO accounts for 80% of desalination systems in operation [2].

3.3 Solar Potential in Texas

Photovoltaic cells are a rapidly growing technology with costs decreasing over time. The price of PV in 1987 was roughly \$9/W but dropped to \$3.65/W by the end of 2008 [12]. The installed, unsubsidized cost for PV system is coming close to \$0.2/kWh [6]. Typical PV levelized cost of energy (LCOE) are in the range of \$0.20-\$0.40/kWh for low latitudes with high insolation of 2,500 kWh/m²/year, \$0.30-\$0.50 /kWh for 1,500 kWh/m²/year (which is typical of Southern Europe), and \$0.50-0.80 per kWh for high latitudes with 1,000 kWh/m²/year [12].

In Texas, the amount of solar energy potential ranges from 872 to 1,310 kWh/m²/year during the winter and from 2,150 to 2,884 kWh/m²/year during the summer [14]. The high end of the range corresponds to the western portion of the state while the low end corresponds to the eastern portion of the state.

Solar panels require little maintenance and can be built in a variety of arrays; making installation relatively easy regardless of the type of space available, given there is enough space. Typically, solar to electric power plants require 5 to 10 acres for every megawatt of generating capacity [10].

3.4 Solar-Powered Desalination

The most common combination of renewable energy and desalination employed worldwide is photovoltaic reverse osmosis and accounts for 31% of renewable energy-powered desalination installation [9]. If solar energy can be located near the desalination plant, using solar panels directly for desalination eliminates the need to incorporate solar energy into the grid, although grid interconnectedness provides support for the system.

The energy intensity of desalinating brackish groundwater has been estimated to be 0.5-3 kWh/m³ [4] while other sources estimate this value to be 1-2.5 kWh/m³ [8]. The energy requirement is proportional to the TDS concentration as well as the depth to the groundwater source. There are currently 44 brackish water desalination plants in Texas, 12 of which use surface water and 32 of which use groundwater [5].

This research will focus on reverse osmosis desalination since the majority of desalination facilities in Texas already utilize this technology. Photovoltaic cells will be the primary focus of solar power generation because PV technology can produce energy from both direct and diffuse radiation as opposed to other concentrating solar power (CSP) technologies which can only make use of the direct radiation. Diffuse radiation is the radiation that is scattered from the direct beam by the atmosphere. The synergistic effects of integrating PV with desalination and using water storage as a proxy for energy storage can advance the implementation of these two technologies. Given existing strain on freshwater along with a wealth of solar and brackish water resources, this research will focus on Texas as a testbed; however, the research methodology and results will be broadly applicable to areas with similar resources and prevailing conditions.

4 Data and Assumptions

Data was obtained from the following two sources:

1. *The Texas Water Development Boards (TWDB) Groundwater Database*. This Microsoft Access database was used to acquire well location coordinates, well depth, and well total dissolved solids (TDS) concentrations for wells with well depths in the range of 100-12,000 feet and TDS concentrations in the range of 1,000-30,000 mg/L. TDS range was selected to correspond to brackish water.
2. *The National Renewable Energy Laboratory's (NREL) National Solar Radiation Database (NSRD)*. Available for download online, NREL data provides monthly and average daily total solar resource averaged over cells of 0.1 degrees in both latitude and longitude, or nearly 10-km in size, using 1998-2005 data and projected using 1983 North American geographic coordinate system. For this research, I focused on the global tilt radiation, which is the total (direct and diffuse) radiation on a tilted surface.

In order to carry out the analysis, the following assumptions were made:

1. *Solar system efficiencies*: The efficiency of solar photovoltaic panels was assumed to be 15% for calculating the power generation from solar PV panels. 15% is an average panel efficiency reported in industry. Concentrating PV technology has higher efficiency.
2. *Pump efficiencies*: A pump efficiency of 65% was assumed based on literature [13].
3. *Specific gravity*: A specific gravity of $9.81 \times 10^3 \text{ N/m}^2$ was assumed for calculating the power requirements of desalination.
4. *Sunlight hours*: It is assumed that there are 6 hours of radiation per day.

5 Methodology

This research was carried out in three phases: determination of the spatial variability of brackish water resources and well characteristic data, determination of the spatial variability of solar radiation, and estimation of the solar-powered desalination capacity across Texas.

5.1 Spatial Variability of Brackish Groundwater Well Characteristics

Brackish water wells with depths in the range of 100-12,000 feet across Texas were mapped in GIS. Locations were provided in decimal degree units and were projected using North American 1983 geographic coordinate system. Using the "Spherical Kriging Interpolation" tool in GIS, the well depth and TDS concentration was estimated for locations across Texas and projected to two different rasters. Using "Extract by Mask" tool and an outline of Texas layer imported from ArcGIS online, the output was fit to Texas. Using the "Project Raster" tool, the rasters were projected to USA Contiguous Albers Equal Area Conic spatial reference in order to preserve the area. This will be important in later use of the rasters with the "Raster Calculator" tool.

5.2 Spatial Variability of Solar Radiation

The national global tilt radiation shape file was obtained from the NREL website and clipped to Texas using the “Clip” tool and Texas outline layer. This was then converted to a raster and projected to USA Contiguous Albers Equal Area Conic spatial reference like in the step above.

5.3 Capacity of Solar-Powered Desalination

The power requirements of desalination by reverse osmosis comprises of the reverse osmosis and pumping power requirements. It is assumed that the desalination facility is located at the well so that power required for the transportation of brackish groundwater is negligible. Thus, the power for desalination can be expressed by this equation [13]:

$$P_{desal} = P_{RO} + P_{pumping}$$
$$P_{desal} = \left(\frac{Q \times \gamma \times WD}{\eta} \right) + (Q \times 0.08 \times (TDS_{in} - TDS_{out}))$$

Where:

P_{desal} = Power needed for desalination, Watts

γ = specific weight of water, N/m³

WD = well depth, meters

η = net efficiency of pump and motor system

TDS_{in} = TDS of feed water, mg/L

TDS_{out} = TDS of treated water, mg/L (desired water quality, 500 mg/L)

Q = volumetric flow rate of water, m³/s

The following expression is used for the calculation of power generation from photovoltaic systems [3]:

$$P_{PV} = \eta_{PV} \times \eta_b \times F_{PV} \times Q_s \times \tau$$

Where:

P_{PV} = operating electrical power

η_{PV} = Efficiency of electrical power operating subsystem

η_b = Efficiency of battery

F_{PV} = surface area of PV modules

Q_s = average daily solar irradiation (W/m²)

τ = average sunny hour

Setting the operating electrical power generated by photovoltaic equal to the power requirements of desalination (pumping and reverse osmosis) and solving for the flow rate, Q (assuming there is no battery included in the PV system) yields the following equation:

$$Q = \frac{\eta_{PV} \times F_{PV} \times Q_s \times \tau}{\left(\frac{\gamma \times WD}{\eta} \right) + (0.08 \times (TDS_{in} - TDS_{out}))}$$

Using the “Raster Calculator” tool in GIS, the well depth, TDS concentration, and solar radiation rasters from the previous two steps in this analysis could be used in the equation to solve for the capacity (as a flow rate, Q). The output is also in raster form. Since the rasters were projected to the same spatial reference in the previous steps, this allowed for the mathematical operations used in raster calculator to be performed on a cell by cell basis.

6 Results

Desalination plants currently in operation in Texas are spread throughout the state (see Image 1 below). Only the northern portion of the state, known as the panhandle, does not have desalination facilities.

Desalination Plant Locations and Design Capacities in Texas

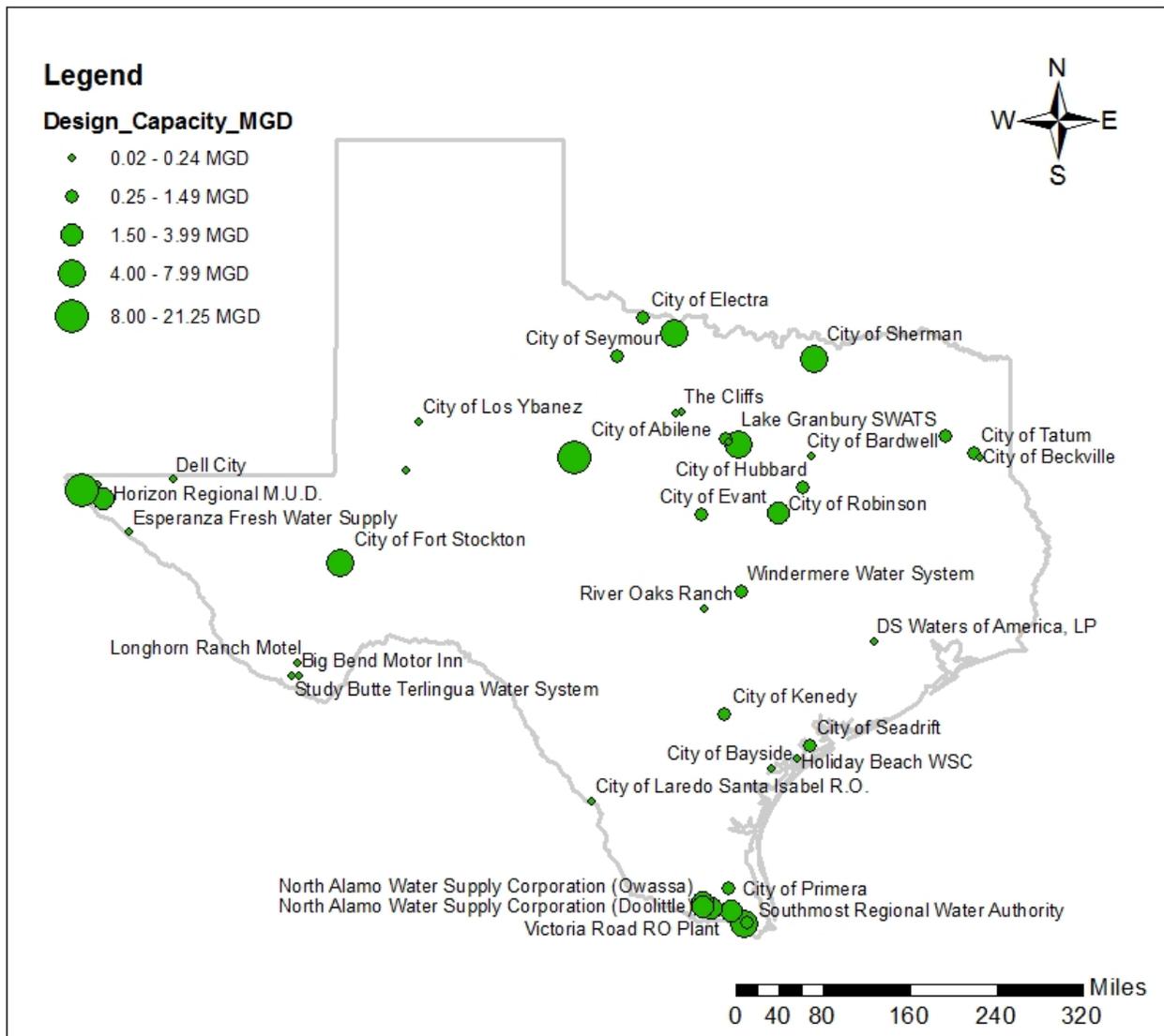


Image 1: Desalination plants and their design capacities in Texas [7].

Brackish water wells with depths in the range of 100-12,000 ft and TDS in the range of 1,000-30,000 mg/L across Texas are depicted on the maps below. Image 2 portrays the wells with greater well depths with larger blue circles and the same wells with the larger red circles representing higher TDS concentrations.

Brackish Groundwater Wells in Texas

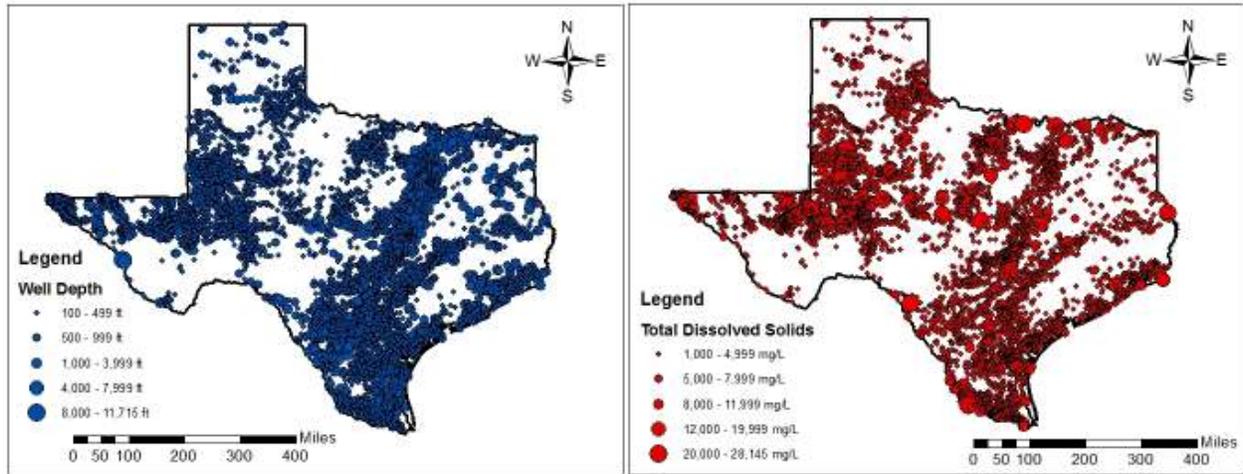


Image 2: Wells in Texas represented by larger blue dots corresponding to larger well depths (left) and larger red dots corresponding to higher TDS concentrations (right).

Wells appear to be concentrated in the southern tip of Texas and along the coast as well in the northwestern portion of the state. Well depth and TDS concentrations seem to be uniformly spread in these regions. The depth and TDS concentrations of the wells was also depicted in graph form by latitude and longitude, as shown in Image 3 and 4 below.

Well Depth across Texas

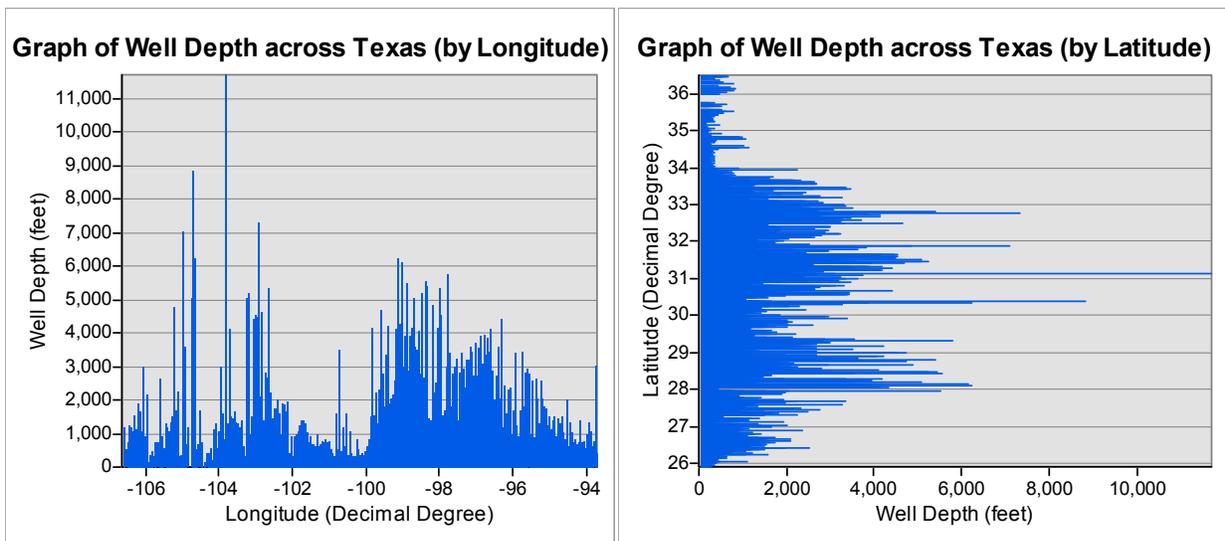


Image 3: Well Depth across Texas depicted by longitude and latitude.

Total Dissolved Solids Concentration across Texas

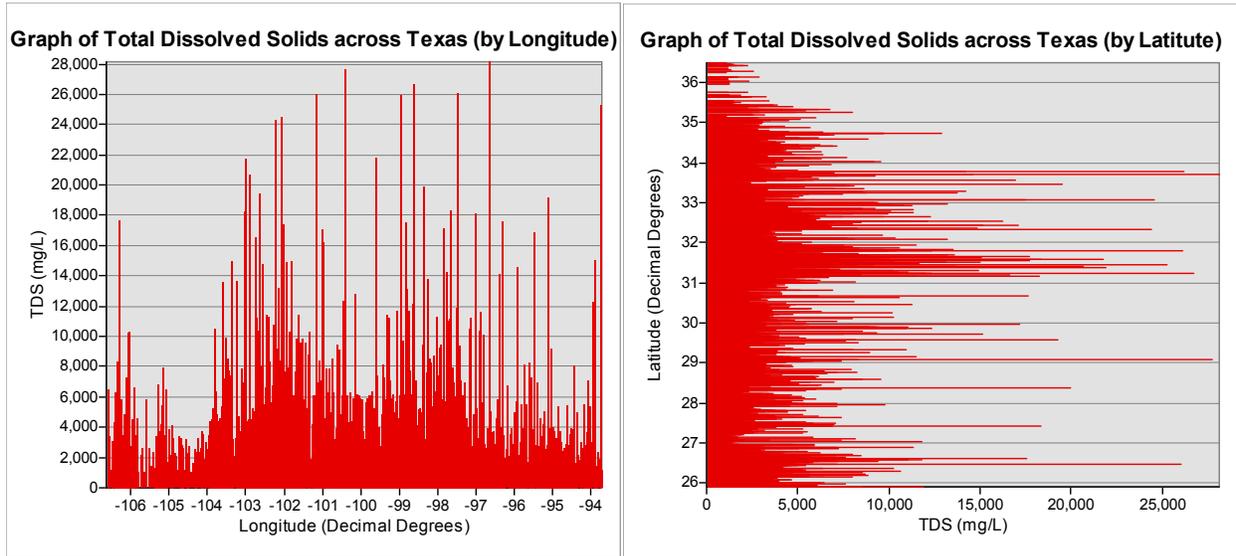


Image 4: Total dissolved solids concentration across Texas depicted by longitude and latitude.

Image 5 shows the distribution of well depth and TDS concentration across Texas determined by Kriging interpolation.

Kriging Interpolation of Well Depth and TDS across Texas

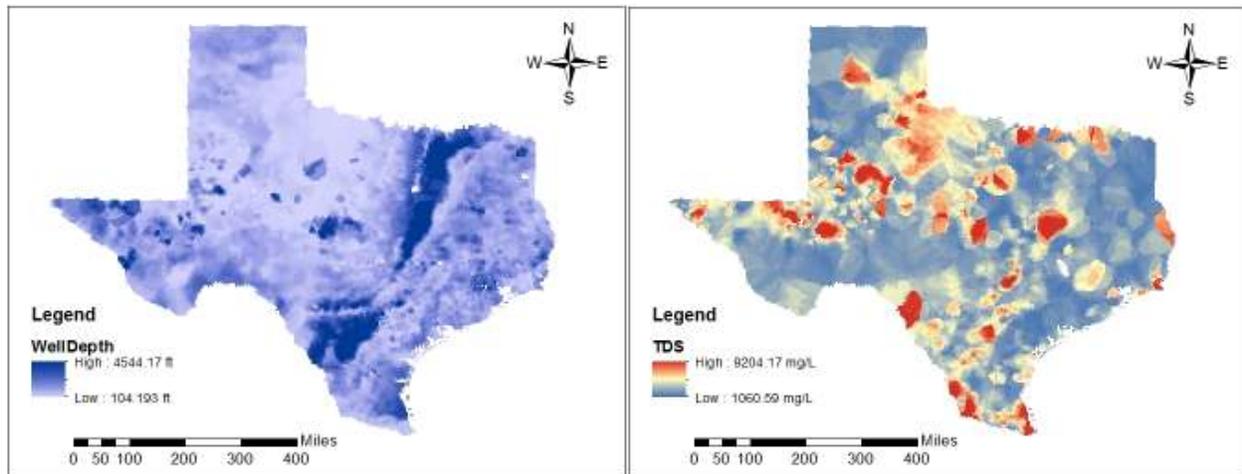


Image 5: Well depth and total dissolved solids concentrations across Texas from interpolation of well characteristic data.

Global tilt solar radiation across Texas is greatest in the western portion of the state, as can be seen in Image 6 below. There is a range from 4.76 kWh/m²/day to 6.58 kWh/m²/day from east to west.

Global Tilt Solar Radiation across Texas

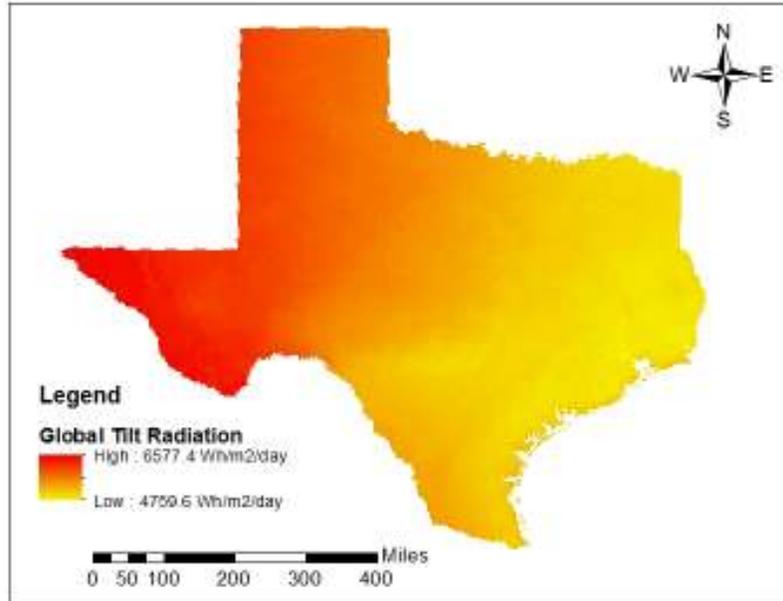


Image 6: Global tilt solar radiation across Texas from NREL's National Solar Radiation Database dataset.

Finally, the capacity that one square meter of PV array could produce was calculated.

Desalination Capacity in Texas

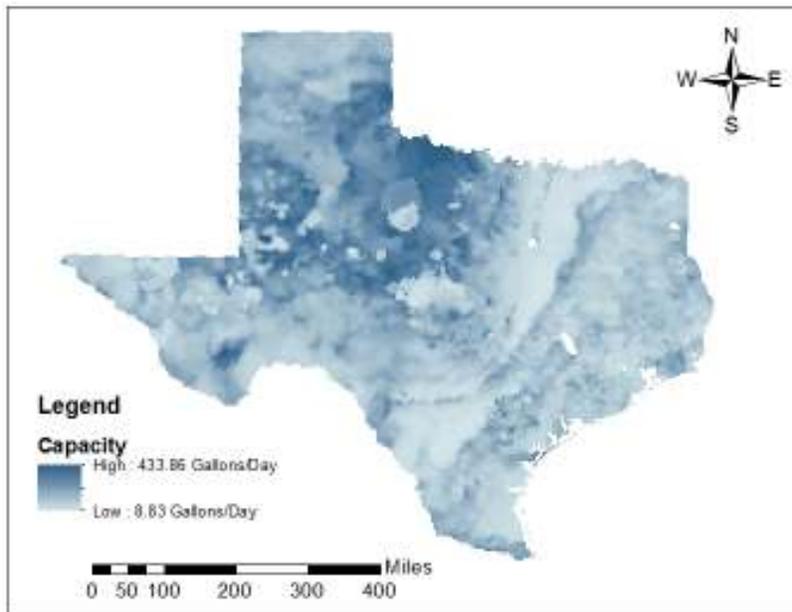


Image 7: Desalination Capacity across Texas calculated using well characteristic and solar radiation data.

7 Discussion and Conclusion

Using the methodology presented herein, a photovoltaic system covering an area of 1 m² is capable of producing roughly 430 gallons/day in some regions of Texas. A desalination facility with a capacity of 1.9 MGD (the average design capacity of desalination plants in Texas) would therefore require a PV array that covers approximately 4,400 m² to supply all of its energy needs if located where optimal conditions are present. These optimal conditions include low well depth, low TDS and high solar radiation. By using photovoltaic to power the pumping and reverse osmosis processes that are a part of desalination, the negative impacts of carbon emissions from such an energy-intensive process are reduced compared to if conventional fossil fuel sources are used. Current focus for efficiency improvements is on balance of systems (BoS) components, such as tracking devices, microinverters, and DC optimizers, to improve power generation from photovoltaic systems which may provide for greater desalination capacity in the future.

This analysis, being performed on a statewide level, crosses many aquifers. The study could be scaled down to individual aquifer level, thereby improving our understanding of individual aquifer characteristics and potential for desalination of brackish water from them. Another consideration that needs to be addressed before implementing new solar-powered desalination facilities is whether there is a sufficient supply of water available at a specific location.

Considering the wide spread of desalination plants currently in Texas, an economic analysis could be performed to determine the cost of installing photovoltaic at desalination facilities currently in operation that meet the optimal conditions set forth in this report. Current operating expenditures and the cost of PV systems can be compared.

Future research might also include analyzing different solar technologies, such as concentrating solar power or solar thermal power. Solar thermal distillation is another potential solar-powered desalination technology worth exploring.

8 References

- [1] Al-Karaghoul, Ali; David Renne; and Lawrence L. Kazmerski. "Technical and Economic Assessment of Photovoltaic-driven Desalination Systems." *Renewable Energy* 35.2 (2010): 323-28. Web. 6 Dec. 2012.
<<http://www.sciencedirect.com.ezproxy.lib.utexas.edu/science/article/pii/S0960148109002626>>
- [2] Arroyo, Jorge; and Saqib Shirazi. "Cost of Water Desalination in Texas." Texas Water Development Board. 16 Oct. 2009. Web. 6 Dec. 2012.
<http://www.twdb.texas.gov/innovativewater/desal/doc/Cost_of_Desalination_in_Texas.pdf>.
- [3] Aybar, H.S., J.S. Akhatov, N.R. Avezova, and A.S. Halimov. "Solar Powered RO Desalination: Investigation on Pilot Project of PV Powered RO Desalination System." *Applied Solar Energy* 46.4 (2010) 275-284. Web. 6 Dec. 2012.
<http://download.springer.com.ezproxy.lib.utexas.edu/static/pdf/39/art%253A10.3103%252FS0003701X10040080.pdf?auth66=1355021188_8da3f797805ab39b263351d3e4966ff5&ext=.pdf>
- [4] Carter, Nicole T. Congressional Research Service Report for Congress, 15 Aug. 2011. Web. 6 Dec. 2012. <<http://www.fas.org/sgp/crs/misc/R40477.pdf>>.
- [5] "Desalination: Brackish Groundwater." Texas Water Development Board. Water For Texas, Jan. 2012. Web. 29 Oct. 2012. <http://www.twdb.state.tx.us/publications/shells/Desal_Brackish.pdf>.
- [6] El-Ghonemy, A.M.K. "Water Desalination Systems Powered by Renewable Energy Sources: Review." *Renewable and Sustainable Energy Reviews* 16 (2012): 1537-556. Academic Search Complete. Web. 6 Apr. 2012.
<<http://www.sciencedirect.com.ezproxy.lib.utexas.edu/science/article/pii/S1364032111005193>>.
- [7] Nicot, Jean-Phillipe; S. Walden; L. Greenlee; and J. Els. "A Desalination Database for Texas." Bureau of Economic Geology. Prepared for Texas Water Development Board. Oct. 2005. Web 7 Dec. 2012. <http://www.beg.utexas.edu/environqlty/desalination/Final%20Report_R1_1.pdf>
- [8] Papadakis, George. ADIRA Handbook: A Guide to Autonomous Desalination System Concepts. European Union. Web. 29 Oct. 2012.
<http://wrrri.nmsu.edu/conf/conf11/2008_adira_handbook.pdf>.
- [9] Papapetrou, Michael; Marcel Weighaus, and Charlotte Biercamp, eds. Pro-Des Project.Roadmap for the Development of Desalination Powered by Renewable Energy. ProDes, 2010. Web. 6 Dec. 2012. <http://www.prodes-project.org/fileadmin/Files/ProDes_Road_map_on_line_version.pdf>.
- [10] "Texas Solar Energy." Solar Energy Conservation Office. Web. 6 Dec. 2012.
<http://www.seco.cpa.state.tx.us/re_solar.htm>.
- [11] United States. Texas Water Development Board. "Water For Texas 2012 State Water Plan." Jan. 2012. Web. 29 Oct. 2012.
<http://www.twdb.state.tx.us/publications/state_water_plan/2012/2012_SWP.pdf>.

[12] United States. U.S. Department of Energy. "2008 Solar Technologies Market Report." National Renewable Energy Laboratory. Jan. 2010. Web. 29 Oct. 2012.
<<http://www.nrel.gov/analysis/pdfs/46025.pdf>>.

[13] Venkataraman, Kartik, Joshua Ortegon, Venkatesh Uddameri, and Rick Dyke. "GIS Based Mapping of Wind-Powered Desalination Potential in South Texas." *AWRA 2012 Spring Specialty Conference*, New Orleans, LA. AWRA, 26-28 Mar. 2012. Web. 6 Dec. 2012.
<http://www.awra.org/proceedings/Spring2012/doc/abs/KartikVenkataraman_208124c8_7917.pdf>.

[14] Wogan, David M.; Michael Webber; and Alexandre K. da Silva. "A Framework and Methodology for Reporting Geographically and Temporally Resolved Solar Data: A Case Study of Texas." *Journal of Renewable and Sustainable Energy* (2010). Rpt. in American Institute of Physics, 2010. Web. 29 Oct. 2012.