ABSTRACT

With a push toward renewable electricity generation, wind power has grown substantially in recent U.S. history and technologies continue to improve. However, the intermittency associated with wind-generated electricity without storage has limited the amounts sold on the grid. Furthermore, continental wind farms have a diurnal and seasonal variability that is mismatched with demand. To increase the broader use of wind power technologies, the development of systems that can operate intermittently during off-peak hours must be considered. Utilization of wind-generated electricity for desalination of brackish groundwater presents opportunities to increase use of a low-carbon energy source and supply alternative drinking water that is much needed in some areas.

As existing water supplies dwindle and population grows, cities are looking for new water sources. Desalination of brackish groundwater provides one potential water source for inland cities. However, this process is energy-intensive, and therefore potentially incongruous with goals of reducing carbon emissions. Desalination using reverse osmosis is a high-value process that does not require continuous operation and therefore could utilize variable wind power. That is, performing desalination in an intermittent way to match wind supply can help mitigate the challenges of integrating wind into the grid while transforming a low-value product (brackish water and intermittent power) into a high-value product (treated drinking water). This option represents a potentially more economic form of mitigating wind variability than current electricity storage technologies. Also, clean energy and carbon policies under consideration by the U.S. Congress could help make this integration more economically feasible due to incentives for low-carbon energy sources.

West Texas is well-suited for desalination of brackish groundwater using wind power, as both resources are abundant and co-located. Utility-scale wind resource potential is found in most of the region. Additionally, brackish groundwater is found at depths less than 150 m, making west Texas a useful geographic testbed to analyze for this work, with applicability for areas with similar climates and water supply scarcity.

Implementation of a wind-powered desalination project requires both economic and geographic feasibility. Capital and operating cost data for wind turbines and desalination membranes were used to perform a thermoeconomic analysis to determine the economic feasibility. The availability of wind and brackish groundwater resources were modeled using geographic information systems tools to illustrate areas where implementation of a wind-powered desalination project is economically feasible. Areas with major populations were analyzed further in the context of existing and alternative water supplies.

Utilization of wind-generated electricity for desalination presents a feasible alternative to energy storage methods. Efficiency, economics, and ease of development and operation of off-peak water treatment were compared to different energy storage technologies: pumped hydro, batteries, and compressed air energy storage. Further economics of compressed air energy storage and brackish groundwater desalination were examined with a levelized lifetime cost approach.

Implementation of water desalination projects using wind-generated electricity might become essential in communities with wind and brackish groundwater resources that are facing water quality and quantity issues and as desires to implement low carbon energy sources increase. This analysis assesses the economic and geographic feasibility and tradeoffs of such projects for areas in Texas.
INTRODUCTION

The diurnal and seasonal variation of some renewable energy options that are expanding rapidly—particularly solar and wind power—presents challenges to resource planners and policy makers. Implementation of carbon-free, domestic, and renewable energy systems is desirable as concerns about global warming, carbon costs, and energy security rise, so it is reasonable to expect that solar and wind installations will continue to proliferate. However, the intermittency of these technologies often does not match with electricity demand. In order to increase use of these technologies, many planners expect that energy storage technologies must be developed to offset the effects of the variability in energy supply.

A seemingly independent issue faced by resource planners and policy makers is the strain on the energy-water nexus. Water sustains cities and rural communities, farms and ranches, and industries. Water is necessary for economic growth. However, water resources can be unpredictable. In addition, many places where water supply sources are diminishing while populations are rapidly growing. Municipalities will have to overcome these challenges by practicing water conservation and/or identifying new water sources. Often, alternative water sources are more remote or are of lower quality. As cities begin to pursue these alternative water supplies for drinking water, additional energy for water collection and conveyance, treatment and disinfection, and distribution to homes will substantially increase electricity consumption in the water sector. For example, desalination of brackish water using reverse osmosis, the most common desalination membrane treatment process, consumes approximately 10 times more energy than traditional surface water treatment [1].

One possible solution to these two independent issues is desalination of brackish groundwater using wind-generated electricity. Since desalination for brackish groundwater is an energy-intensive process that can be operated intermittently, the utilization of wind-generated electricity to power the process prevents emissions of additional air pollutants associated with energy production from fossil fuel sources and introduces a more valuable use of this variable energy source. However, this solution faces a challenge in that both desalination membrane equipment and wind turbines have high capital costs. Therefore, the fixed and variable costs must be carefully analyzed prior to implementation of an integrated system to determine the potential profitability.

This case study uses capital and operating cost data for desalination membranes and wind turbines to conduct a thermoeconomic analysis, applying the laws of thermodynamics to economic theory. The energy required to desalinate brackish groundwater is modeled as a function of total dissolved solids (TDS) and depth to water table. The availability of resources is modeled using geographic information systems tools to illustrate areas where implementation of a wind-powered desalination project is economically and technologically feasible. Areas of feasibility are found to be concentrated in the Panhandle region of West Texas. The major populations located within these areas are the cities of Lubbock, Midland, and Abilene. Municipal water end uses are analyzed for these cities in the context of existing and alternative water supplies.

Utilization of wind-generated electricity for desalination presents an alternative to conventionally thought-of energy storage methods. In order to demonstrate the economic and technological advantages, off-peak water treatment is benchmarked against compressed air energy storage, pumped hydro, and batteries. Efficiency, ease of operation, and economics are considered. A levelized lifetime cost approach is used to further demonstrate the economics of off-peak brackish groundwater desalination and compressed air energy storage technologies.

BACKGROUND

Wind Power

Due to concerns of global climate change, instability of fossil fuel prices, and energy security, the last decade has witnessed substantial growth in renewable energies including wind power. At the end of 2010, the installed wind electricity generation capacity in the United States was just over 40,000 MW. Texas has a larger installed wind turbine capacity than any other state, with a total of 10,000 MW [2]. Despite the significant increase in wind turbine installations, this technology only accounts for 2.3 percent of the total electricity generating capacity of the United States [3]. Although wind resources are abundant throughout the U.S., the inherent variability inhibits the growth of this technology.

Wind resources are subject to diurnal (daily) and seasonal variations as well as intermittency. An occurrence in February of 2007 when wind generation from West Texas dropped from 1700 MW to 300 MW in only hours demonstrates the intermittency of this resource. Although the drop was predicted, the Electric Reliability Council of Texas (ERCOT) faced challenges in avoiding major blackouts and electricity disruptions because ancillary service providers were not available [4]. Furthermore, wind is mismatched with peak electricity demand. As seen in Figure 1, wind in West Texas is out of phase with demand in ERCOT load over a typical summer day. When demand is highest in the afternoons, wind is at its weakest and when demand is at its lowest in the night, wind reaches its peak. The intermittency of wind and mismatch with electricity demand demonstrates the value of energy storage.
Desalination

Treating brackish groundwater or seawater to potable water standards requires some desalination process to remove total dissolved solids, generally salts and minerals. Large-scale desalination typically consumes extremely large amounts of energy and requires specialized, expensive infrastructure, making it very costly in comparison to use of fresh water from rivers or groundwater. Traditional desalination technologies that are considered reliable and established processes include reverse osmosis, multi stage flash, multi effect distillation, and electrodialysis [6]. Reverse osmosis, the most common of these processes, applies pressure to the solution when it is on one side of a selective membrane. The solute is retained on the pressurized side of the membrane while the permeate is allowed to pass to the other side. Reverse osmosis processes are usually arranged in a cascade fashion to improve the recovery of permeate of fresh water. Recovery of reverse osmosis treatment for brackish water ranges from 50 to 90 percent, depending on water quality and operating parameters [1].

Historically, desalination processes are used to provide drinking water only in areas of the world with abundant inexpensive energy and scarce freshwater, such as Saudi Arabia. An increasing number of coastal cities are beginning to desalinate seawater due to decreasing freshwater sources. Since 2004, a brackish groundwater plant in El Paso has been producing fresh water by reverse osmosis. This plant produces 100,000 m$^3$ of fresh water daily, about 25 percent of total freshwater consumption, for this water-stressed city [7]. Yet, in 2006 worldwide desalination capacity totaled only 37 million m$^3$/day, about 0.3 percent of global freshwater consumption [1].

In addition to the energy-intensity and high costs, brackish groundwater desalination for inland locations has the challenge of concentrate disposal. While coastal desalination locations have the luxury to dispose waste streams with concentrated salts into the ocean or gulf through dispersion, inland locations must dispose of this concentrate in other ways. Current options for concentrate disposal include sewer or surface water discharge after wastewater treatment processes, evaporation ponds, and deep well injection [8]. These disposal options are often costly and must be monitored carefully to ensure land and other water supplies are not contaminated and to reduce adverse environmental effects. In order to better manage the challenges of concentrate disposal, researchers have aimed at improving overall recovery by minimizing concentrate waste streams. Electro dialysis, another energy intensive process, is one approach to further treat the concentrate stream and recover additional product water, reducing the volume of concentrate that requires disposal [8].

Integrated Wind and Desalination Technology

The rising concern over greenhouse gas emissions and dwindling water supplies has already resulted in the integration of wind-generated electricity and desalination. The wind-powered, Perth Seawater Reverse Osmosis Plant in Australia opened in November 2006. An 80 MW wind farm, consisting of 48 wind turbines powers the plant and yields approximately 9.4 m$^3$ of drinkable water every minute [9]. This plant demonstrates this integration is technically feasible and for water strained areas, economically feasible. Additionally, pilot-scale tests are underway to use wind-generated electricity for brackish groundwater desalination at Texas Tech University. The program aims to develop a wind-powered desalination plant to supply water for the 10,000 residents of Seminole, Texas [10].

However, there are challenges associated with the integration of wind power and desalination technologies. The specialized infrastructure of wind turbines and reverse osmosis membranes make these technologies capital intensive in comparison to other electricity generation facilities and traditional water sources. The intermittent wind combined with water demand and electricity generation creates a complex model for process control. Although reverse osmosis membranes can operate intermittently, process parameters must be optimized to prevent excessive wear on membranes [11]. Also, if not extracted sustainably, groundwater resources are an exhaustible source.

Although there are challenges to be overcome with the integration of wind-generated electricity and desalination, there are also many advantages. Generally, there is no competition for access to brackish groundwater as it is unusable for agricultural irrigation due to high levels of total dissolved solids. Desalination is an energy-intensive process that would introduce significant air emissions if powered by fossil fuels. The use of wind power eliminates associated air emissions as...
well as fuel costs by utilizing a renewable source. Consequently, wind-powered desalination produces a high-value product (drinking water) from a previously unusable source (brackish groundwater) using energy that cannot be dispatched on demand and produces no air emissions (wind-generated electricity without storage).

**TEXAS AS A CASE STUDY**

Suitable wind classifications for utility-scale wind turbines and prevalent brackish groundwater makes Texas an appropriate setting for this case study. In addition, populations and water needs in Texas are growing, yet estimates show that existing water supplies are dwindling. Consequently, water resource managers might need to consider water supplies previously considered unusable, such as brackish groundwater.

Wind resources provide one alternative to traditional fossil fuel-generated electricity. With 10,085 MW of installed wind power capacity at the end of 2010, Texas far outpaces every other state regarding the amount of installed wind capacity. No state has matched the rate at which Texas has installed wind turbines over the last five years [2]. This record demonstrates the value of Texas as a testbed for investigation of technologies to integrate with wind power generation. Typically, a wind class of 3 or greater is considered to be profitable for generating energy with large wind turbines. As shown in Figure 2, wind resources are also prevalent in Texas; more specifically the panhandle region has a wind power classification of 3 and 4 [12]. Furthermore, if energy prices rise, or if costs for wind turbines fall, the wind power classification considered profitable could decrease and more areas of Texas could be considered for wind power generation.

The Texas Water Development Board (TWDB) developed regional water plans to quantify current and projected population and water demand, evaluate and quantify current water supplies, identify needs, and adopt water management strategies. TWDB expects a 27 percent increase in Texas’s population from about 21 million in 2000 to 45 million in 2060. The demand for water is expected to increase 27 percent from almost 21,000 million m$^3$ in 2000 to 26,600 million m$^3$ in 2060. Existing water supplies are projected to decrease about 18 percent from 22,000 million m$^3$ in 2000 to 18,000 million m$^3$ in 2060. Existing water supplies includes all amounts of water that can be produced during drought with current permits, current contracts, and existing infrastructure. These estimates reveal a potential need of an additional 8,600 million m$^3$ by 2060 from new water supplies [14].

The TWDB has identified many water management strategies and projects to generate additional water supplies for Texas, including desalinization of brackish groundwater in some areas [14]. These projects are feasible only in locations where brackish groundwater wells are accessible. Figure 3 demonstrates that brackish groundwater is prevalent in much of Texas. Water is considered brackish when total dissolved solids exceed 1,000 mg/L. Although, this resource has traditionally been viewed as unusable because of the energy-intensity and environmental impacts of the process to treat it to potable standards, strained water supplies in some Texas cities, such as El Paso, have led to implementation of brackish groundwater desalination plants for drinking water supply.

As a result of the increasing water supply needs and installed wind capacity and the availability of brackish groundwater and wind resources, Texas is a suitable case study for evaluating the thermoeconomic feasibility.
of using wind-generated electricity for brackish groundwater desalination.

METHODOLOGY
The thermoeconomic and geographic feasibility of implementing a brackish groundwater desalination plant using wind-generated electricity is evaluated using well characteristic parameters, integration parameters, and geographic parameters. These parameters are presented as operational questions a planner, manager, or policy maker might ask prior to deciding whether to proceed with using wind power for desalination and at certain locations.

Previous research by the authors used similar methodology for determining parameters and locations of economic feasibility [16]. Previous research did not include consideration of water quality while this analysis considers the embedded energy in desalination as a function of water quality expressed as total dissolved solids.

The thermoeconomic analysis performed is based on both fixed and variable costs reported in literature for wind power and brackish groundwater desalination and are summarized in Table 1 [16]. Cost values are adjusted to 2008 dollars using the Consumer Price Index (CPI) from the Department of Labor Bureau of Labor Statistics [25]. Constructing wind turbines and reverse osmosis facilities are capital intensive and operating desalination facilities is also costly when including costs for electricity consumption. The ranges in costs are wide to account for uncertainty in materials available, technology, operations, and financing options. Additionally, Texas average retail values of $0.11/kWh and $1.17/m³ for electricity and water, respectively, are used to estimate revenues [26,27].

The availability of resources and profitability are modeled using geographic information systems (GIS) tools to illustrate areas in Texas where implementation of this integration is economically feasible. In order to perform this geographic analysis, two datasets are used:

- Brackish groundwater wells: The dataset from the Texas Water Development Board (TWDB) provides location, depth, and water quality of Texas brackish groundwater wells [15].
- Wind power classification: The dataset from the Alternative Energy Institute (AEI) provides wind energy potential as a GIS raster file [13]. Wind power classifications are based on wind power density and wind speeds at both 10 m and 50 m [14].

<table>
<thead>
<tr>
<th>Description</th>
<th>Reported Costs (2008S)</th>
<th>Units</th>
<th>Analysis Equations* (2008S)</th>
<th>Parameters</th>
<th>Units</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wind turbine (installed)</td>
<td>$1,450</td>
<td>$/kW</td>
<td>$C_{wt} = 2.13P_{wt}$</td>
<td>$P_{wt}$</td>
<td>$</td>
<td>[17]</td>
</tr>
<tr>
<td>Power transmission</td>
<td>$1,120</td>
<td>$/m</td>
<td>$C_{tr} = 0.215P_{wt} \times (6.53)$</td>
<td>$P_{wt}$</td>
<td>$</td>
<td>[18]</td>
</tr>
<tr>
<td>Wind operations &amp; maintenance</td>
<td>$3$</td>
<td>$/MWh</td>
<td>$C_{WOB&amp;M} = -8.41 \times 10^{-12}P_{wt}^2 + 7.68 \times 10^{-4}P_{wt} + (-2.18)$</td>
<td>$P_{wt}$</td>
<td>$</td>
<td>[17]</td>
</tr>
<tr>
<td>Reverse osmosis equipment &amp; facility</td>
<td>$510$</td>
<td>$/m^3/d$</td>
<td>$C_{RO} = 8.08 \times 10^7q $ \times (6.66)$</td>
<td>$q$</td>
<td>$</td>
<td>[19,20]</td>
</tr>
<tr>
<td>Groundwater well</td>
<td>$116,000$</td>
<td>$/d$</td>
<td>$C_{gww} = 7.38 \times 10^4 + 883z$</td>
<td></td>
<td>$</td>
<td>[21]</td>
</tr>
<tr>
<td>Treated water distribution</td>
<td>$196$</td>
<td>$/d$</td>
<td>$C_{wa} = 33.3L + 15.2D^{1.54}L$</td>
<td></td>
<td>$</td>
<td>[22]</td>
</tr>
<tr>
<td>Reverse osmosis operations &amp; maintenance*</td>
<td>$0.09$</td>
<td>$/m^3$</td>
<td>$C_{ROO&amp;M} = 26,600q^2 + 7060q$</td>
<td>$q$</td>
<td>$</td>
<td>[20,23]</td>
</tr>
<tr>
<td>Brackish water</td>
<td>$0.05$</td>
<td>$/m^3$</td>
<td>$C_{bgw} = 5010q$</td>
<td></td>
<td>$</td>
<td>[24]</td>
</tr>
</tbody>
</table>

*Adapted from literature source, unless noted. See Nomenclature for appropriate variable units.
†Statistics from authors’ linear regression shown, with t-statistics for coefficients in parentheses. Insignificant coefficients were deleted.
*Does not include electricity costs due to system vertical integration.
Areas are determined economically feasible or infeasible based on two criteria: wind power classification and brackish groundwater desalination profitability. Areas with a wind power classification of 3 or higher are considered suitable for utility-scale wind turbines [12]. Profitability of desalination is calculated as the total costs, TC, minus the total revenue, TR, as in Equations 1 and 2.

The total cost calculated represents the cumulative fixed and variable costs incurred over the time of operations, t, as shown in Equation 1. This equation is adopted from reported cost values of wind turbine, power transmission, reverse osmosis equipment and facility, groundwater well, treated water distribution and operations and maintenance costs for both wind and reverse osmosis, shown in Table 1.

\[
TC = 2.35P_{wt} + 8.08 \times 10^{-7}q + 33.3L + 15.2d^{1.54}L + 883z + 7.38 \times 10^{6} + t(-8.41 \times 10^{-12}P_{wt}^{2} + 7.68 \times 10^{-4}P_{wt} + 26,600q^{2} + 12,100q) \tag{1}
\]

Definitions of the variables in all equations are given in the Nomenclature section.

The total revenue over the period of operations is based on treated water sales, as shown in Equation 2.

\[
TR = \$1.17\eta_{ro}qt \tag{2}
\]

The total cost is dependent on the power rating of the wind turbine, \(P_{wt}\). The \(P_{wt}\) is based on the power requirements for pumping water from the aquifer and in pipelines, \(P_{p}\), and the power requirements for brackish groundwater desalination, \(P_{D}\), shown in Equation 3.

\[
P_{wt} = P_{p} + P_{D} \tag{3}
\]

The power requirement for pumping is based on the depth to aquifer, \(z\), and pipe length, \(L\), as shown in Equation 4. This equation was developed using the Darcy-Weisbach equation for head loss in pipes.

\[
P_{p} = \frac{\rho g}{
\eta_{p}C_{w}} \times \left( z + \frac{q_{p}^{2}}{2g} \left( \frac{f}{d} (z + L) \right) \right) \tag{4}
\]

The power requirement for desalination is a function of the energy required for desalination, \(E_{D}\), which is a function of the total dissolved solids (TDS) of the water and the flow rate, \(q\), shown in Equation 5. Water is considered brackish for values of 1,000 to 3,500 mg/L TDS. The national average electricity use for brackish groundwater water treatment is 3,900 to 9,700 kWh/Mgal [28]. \(E_{D}\) is modeled as a linear function of TDS based on the range of electricity use.

\[
P_{D} = E_{D}(TDS) \times q \tag{5}
\]

The brackish groundwater well dataset from TWDB provides the depth and water quality (total dissolved solids) used in these calculations [15]. Volumes of water by well are not available, however, TWDB is currently working to quantify these volumes. Therefore, it is assumed that wells have the sufficient volume of brackish water necessary for a desalination facility.

The following assumptions are made to determine the total profit:

- Pump efficiency of 60 percent.
- Reverse osmosis recovery of 70 percent.
- Interest of 10 percent for financing capital equipment.
- Initial depth to brackish groundwater of 1.22 m, the minimum brackish well depth in Texas [15].
- Water table drop of 1.5 m per year such that pumping depths increase as brackish groundwater is withdrawn from the aquifer.

Some overall facility assumptions are made in order to analyze the integration of desalination and wind-generated electricity. First, the reverse osmosis treatment capacity of the wind-powered desalination facility is assumed to be 3,785 m³/d (0.0438 m³/s). Average recovery, the ratio of produced water flow to incoming flow, for brackish water reverse osmosis is 70 percent [1]. These assumptions were made to produce 2,650 m³ of drinking water, which could provide enough water for 5,000 people each using 0.53 m³ per person per day, a water conservation goal set by the Texas Water Conservation Implementation Task Force [26]. The wind turbines and the desalination facility are assumed to operate as a single firm such that electricity costs for desalination are zero. Land is assumed to be leased and brackish groundwater is purchased from a landowner. The right of capture governs groundwater law in Texas such that landowners may pump water beneath their property [29]. Land purchase is not required.

After modeling the areas of economic and technical feasibility, counties that contain major cities within these areas are examined further. Current and future population, water demand, and water supply of these counties are examined to better gauge whether a wind-powered brackish groundwater desalination facility is practical. Because volume of brackish water per well is not provided, the brackish groundwater availability for the aquifers contained in these counties is examined.

Finally, in order to demonstrate wind-generated electricity desalination as a feasible alternative to energy
storage methods, pumped hydro, batteries, and compressed air energy storage technologies are examined. Efficiency, ease of operation, and economics are considered. A levelized lifetime cost approach is used to further demonstrate the economics of off-peak brackish groundwater desalination and compressed air energy storage technologies. This method takes into account all capital, operation and maintenance, fuel, and water costs. Transmission and distribution are not included. With these costs estimates and appropriate values for the discount rate, technical lifetime, and plant capacity factor, the levelized cost of energy, LCOE, and levelized cost of water, LCOW, can be calculated. Reported values for LCOE of a CAES plant were found, while the LCOW for a wind-powered brackish groundwater desalination plant were calculated, based on Equation 6, 7, and 8. These parameters demonstrate wind-powered desalination as a feasible alternative.

\[
CAPEX [\$/m^3] = \left(\frac{\text{CAPEX} [\$/m^3]}{(1+d)^N}\right) \left(\frac{1}{365[\text{yr}]}\right) \left(\frac{\text{CF}}{\text{CF}}\right)
\]

\[
OPEX [\$/m^3] = \text{Usually quoted in } \$/m^3
\]

\[
LCOW [\$/m^3] = CAPEX + OPEX
\]

In order to calculate the LCOW of off-peak desalination, the following assumptions are made:

- A discount rate of 5 percent, which is consistent with International Energy Agency’s (IEA) Energy Technologies Perspectives 2006 report [30].
- A technical lifetime of 25 years.
- Plant capacity factor of 25 percent, based on the wind capacity factor of 33 percent [31].
- Waste disposal costs are excluded.

RESULTS

In order to demonstrate the level of effect brackish groundwater well characteristics has on the profitability of desalination, profitability is graphed for a range of values for depth and water quality. As seen in Figure 4, higher profitability is found for shallow depths and low total dissolved solids. Due to the energy intensity of pumping, the depth of the well has a much larger impact on profitability than the total dissolved solids when considering brackish groundwater.

![Figure 4. Brackish water well characteristics, depth and quality, impact the profitability of desalination.](image)

These economical feasibility parameters were used in determining geographic feasibility of a brackish groundwater desalination facility using wind-generated electricity.

LOCATIONS OF FEASIBILITY

ArcGIS was used to determine areas of overall feasibility, based on profitability and technical achievability. In Texas, profitable brackish groundwater wells exist in areas of wind power classification of 3 or higher, therefore location of technical feasibility exist in Texas. Figure 5 displays that areas of feasibility are concentrated in the Panhandle region of West Texas. The major populations located within these areas are the cities of Lubbock, Midland, and Abilene. These cities are located in Lubbock, Midland, and Taylor County, respectively. Wind power classification from AEI and average well characteristics of TDS and depth from TWDB of these areas produce high average profitability estimates, as shown in Table 2. The average profitability listed here is the total revenue minus the total costs for a 10 year operating period.

<table>
<thead>
<tr>
<th>County</th>
<th>Wind Class</th>
<th>Avg. TDS</th>
<th>Avg. Depth</th>
<th>Avg. Profitability (10 yrs operation)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lubbock</td>
<td>3</td>
<td>1375</td>
<td>30 m</td>
<td>$3,860,000</td>
</tr>
<tr>
<td>Midland</td>
<td>3</td>
<td>1685</td>
<td>35 m</td>
<td>$3,650,000</td>
</tr>
<tr>
<td>Taylor (Abilene)</td>
<td>3</td>
<td>1560</td>
<td>8 m</td>
<td>$4,070,000</td>
</tr>
</tbody>
</table>
Figure 5. Areas of profitable brackish groundwater desalination using wind-generated electricity are found in West Texas. The cities of Lubbock, Midland, and Abilene are located within areas of profitability.

The major and minor aquifers in each county were examined to explore the brackish groundwater availability. Lubbock County contains the Ogallala Aquifer, Edwards-Trinity (High Plains) Aquifer, and Dockum (Santa Rosa) Aquifer. Midland County contains the Edwards-Trinity Aquifer, Ogallala Aquifer, and Dockum (Santa Rosa) Aquifer. Taylor County contains the Edwards Aquifer, Trinity Plateau Aquifer, and Trinity Aquifer [15]. Each of these aquifers extends over multiple counties, approximately 40. TWDB estimates that these aquifers contain large volumes of brackish groundwater, which suggests that the wells analyzed are suitable for desalination facilities, as shown in Table 3. Estimated volume of brackish groundwater “in place” is defined as the estimated total amount currently in unconfined storage in the aquifer [21].

Table 3. Estimated volumes of brackish groundwater in aquifers suggest suitable amounts of water are available for desalination [21].

<table>
<thead>
<tr>
<th>Aquifer</th>
<th>Estimated Volume &quot;In Place&quot; (million m$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dockum (Santa Rosa) Aquifer</td>
<td>153,830</td>
</tr>
<tr>
<td>Edwards-Trinity (High Plains)</td>
<td>7,180</td>
</tr>
<tr>
<td>Edwards-Trinity Plateau</td>
<td>29,890</td>
</tr>
<tr>
<td>Trinity</td>
<td>219,390</td>
</tr>
<tr>
<td>Ogallala</td>
<td>44,680</td>
</tr>
</tbody>
</table>
The TWDB performed an analysis and produced a report, *Water for Texas*, on the water needs and necessary management strategies for current and future water demands for each region and county. As shown in Table 4, the population, total water needs, and municipal water needs for each county are expected to grow substantially from 2010 to 2060. Currently, 97 percent of the Lubbock area water supply is groundwater from the Ogallala Aquifer; however, the existing supply of groundwater is significantly decreasing and the area might need to turn to lower quality or more expensive water sources. The Midland County area also relies heavily on groundwater, while the Taylor County water supply consists more of surface water. In order to help meet the expected growth in demand with decreasing existing supply, desalination of brackish groundwater is suggested as a water management strategy was suggested for both Midland County and Lubbock County. TWDB estimates that 20 million m³/year of water can be supplied to Midland and surrounding areas through brackish groundwater desalination for a total capital cost of $131 million and estimated annual average cost of $0.49/m³ for Lubbock and surrounding areas, TWDB estimates 4.1 million m³/year can be supplied with capital costs of $10 million and annual average unit cost of $0.41/m². No suggestions of desalination are made for Taylor County and surrounding area [14].

### Table 4. Population, total water needs, and municipal water needs are expected to increase between 2010 and 2060 in the counties of Midland, Lubbock, and Taylor [14].

<table>
<thead>
<tr>
<th></th>
<th>2010 Population</th>
<th>2060 Population</th>
<th>2010 Total Water Needs (million m³)</th>
<th>2060 Total Water Needs (million m³)</th>
<th>2010 Municipal Water Needs (million m³)</th>
<th>2060 Municipal Water Needs (million m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Midland</td>
<td>265,550</td>
<td>303,860</td>
<td>27.4</td>
<td>47.6</td>
<td>7.4</td>
<td>27.9</td>
</tr>
<tr>
<td>Lubbock</td>
<td>124,710</td>
<td>151,660</td>
<td>87.0</td>
<td>138.6</td>
<td>4.8</td>
<td>19.8</td>
</tr>
<tr>
<td>Taylor (Abilene)</td>
<td>136,370</td>
<td>139,310</td>
<td>15.7</td>
<td>15.6</td>
<td>15.7</td>
<td>15.6</td>
</tr>
</tbody>
</table>

**PROXY FOR ENERGY STORAGE**

The intermittency, occasional unexpected interruptions, and mismatch with demand of wind power limit the implementation of this technology. One way to overcome these issues is to incorporate energy storage to allow wind energy to be used on a dispatchable, load-balancing basis. Wind energy storage technologies were explored as a benchmark against wind power for brackish groundwater desalination. Three practical and deployable energy storage methods were explored: pumped hydroelectric energy storage (PHS), batteries, and compressed air energy storage (CAES).

**Pumped Hydro Storage**

Pumped hydro utilizes potential energy in the form of water raised to an elevation. The main components of a pumped hydro system include turbine/generator equipment, a waterway, an upper reservoir, and a lower reservoir. When inexpensive energy is available, water is pumped to the reservoir at a higher elevation. The water is later released when energy is at a higher demand and is more valuable. The water goes through the turbine, which turns the generator to produce electric power. While these facilities are net energy consumers due to the energy requirements of the pumping process, operators generate revenue by utilizing the electricity price variation throughout the day. This storage technology is mature with over 100 operating facilities worldwide and can be rapidly switched on and off. The round trip efficiency of PHS is estimated to be 75 to 80 percent [32]. However, locating a site for a PHS facility presents a sizable challenge, as two critical terrain characteristics are required. First, access to large volumes of water is needed in order to store a useful amount of potential energy. The Ludington PHS facility, located on the bank of Lake Michigan, holds approximately 27 billion gallons of water with a generating capacity of 1,870 MW [33]. Second, the site must contain a large elevation change to create the lower and upper reservoirs. At the Ludington PHS facility, water is pumped 363 feet uphill in order to achieve a substantial potential difference [33]. Although PHS facilities provide load-leveling power, locating a site with these two critical terrain characteristics in West Texas is unlikely.

**Batteries**

For centuries, batteries have been a common energy storage source for many household and industrial applications. Recent advancements in battery life, capacity, charging, and performance have helped battery technology progress rapidly. Several types of batteries that are currently available include lead-acid, nickel/cadmium, zinc/bromine, lithium-ion, and vanadium-redox [34]. A battery’s characteristics may vary over load cycle, charge cycle, and lifetime based on the internal chemistry, current drain, and temperature. The quick ramping capability of batteries is useful to the electric grid [35]. The round trip efficiency of battery energy storage is estimated to be between 60 and 85 percent [32]. Small scale applications of this technology are widespread. However, this technology at its current development is not
considered usable for industrial scale energy storage because of the high cost.

**Compressed Air Energy Storage**

Compressed air energy storage (CAES) facilities are similar to a typical natural gas power cycle with the addition of air storage and the decoupling of the compressor and turbine. CAES facilities compress air into storage using inexpensive energy and later release the air into a combustion turbine generator system when energy is at a higher price. For larger capacity CAES plants, compressed air is stored in underground geological formations. There are currently two CAES facilities in operation, the first in Germany and the second in Alabama. Both plants use natural gas-fired combustors to heat the compressed air before expansion. The round trip efficiency of CAES is estimated to be 73 to 80 percent [34]. An integrated system has been proposed to combine wind and solar energy with compressed air and thermal storage techniques in a way that couples excess wind capacity at night and peak solar during the day [36].

The capital costs and operations costs for each technology, wind turbines, and a reverse osmosis desalination facility allow for a first-look economic comparison, as seen in Table 5. For energy storage, batteries show the highest capital and operations and maintenance (O&M) costs, followed by pumped hydro and CAES. A direct comparison of storage technologies to desalination is difficult as they are based on production of two different products, electricity and water.

As previously discussed, the round trip efficiencies for pumped hydro, batteries, and CAES are 75-80 percent, 60-85 percent, and 73-80 percent, respectively [32]. The efficiency of desalination plants is measured in recovery, the ratio of product water to input water and is 50-90 percent [1]. For traditional energy storage systems the product in and out is energy in the form of electricity, while for the proposed project the input products of energy and brackish groundwater are transformed into energy stored in the form of a high value product, desalinated water. Therefore, the efficiencies cannot be compared directly. The economics of CAES and off-peak desalination are examined further as both technologies are most fit for locations in West Texas.

The LCOW for wind-powered brackish groundwater desalination was calculated as $0.76/m^3, while a reported value of LCOE for an integrated CAES was found to be $85/MWh ($0.085/kWh) [36]. Although a direct comparison of LCOW and LCOE can not be made, each can be compared to expected revenues. Texas average retail values for water and electricity are $1.17/m^3 and $0.11/kWh, respectively [26,27]. Therefore, the wind-powered brackish groundwater desalination facility is expected to profit $0.41 per m^3 of water produced. The CAES plant is expected to profit $0.025 per kWh of electricity produced. As water and electricity are different commodities, the profit alone is not the deciding factor for which wind powered integration to install. The current and expected need of a commodity should drive the development of a technology.

**CONCLUSIONS AND POLICY IMPLICATIONS**

In order to increase use of intermittent wind technologies, many planners expect that energy storage technologies must be developed to offset the effects of the variability in energy supply. One new way to think of energy storage is the storage of energy in the form of high value products, such as desalinated brackish groundwater.Concern over air emissions has led many resource planners and policy makers to carefully weigh options when considering energy-intensive processes such as desalination. However, in response to decreases in current water supply coupled with growing populations, Texas cities are considering more energy-intensive water sources. Brackish groundwater desalination using wind-generated electricity keeps this energy-intensive project emissions-free while providing a new supply of water from a source previously considered unusable.

Brackish groundwater desalination using wind-generated electricity is both economically and technologically feasible in areas of West Texas. High profitability of this integration exists around the populated cities of Abilene, Lubbock, and Midland. These cities have growing populations, decreasing existing water supply, and increasing water demand.

Brackish groundwater desalination using wind-generated electricity provides a feasible alternative to energy storage technologies. Pumped hydro is not fit for West Texas because of the large volumes of water and elevation change required. Batteries have high capital costs and small capacities. CAES provides an option of wind energy storage for West Texas as it is both economically and geographically feasible. Further economic analysis based on levelized costs demonstrates both CAES and off-peak desalination are feasible options. A LCOE value of $85/MWh has been reported for CAES and the average retail value of

<table>
<thead>
<tr>
<th>Source</th>
<th>Reported Capital Costs</th>
<th>Reported O&amp;M Costs</th>
<th>Wind</th>
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<tbody>
<tr>
<td></td>
<td>$/kW</td>
<td>$/MWh</td>
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<td>Pumped Hydro</td>
<td>2130</td>
<td>8</td>
<td>[16]</td>
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<tr>
<td>Batteries</td>
<td>1710</td>
<td>7.4</td>
<td>[37]</td>
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<tr>
<td>CAES</td>
<td>2075</td>
<td>12</td>
<td>[37]</td>
</tr>
<tr>
<td>Desalination</td>
<td>946</td>
<td>4.6</td>
<td>[37]</td>
</tr>
<tr>
<td></td>
<td>735</td>
<td>0.14</td>
<td>[18,19]</td>
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</table>
electricity is $0.11/kWh [37, 27]. The LCOW for wind-powered brackish groundwater desalination was calculated as $0.76/m³ and the average retail value of water is $1.17/m³ [26].

As cities continue to grow and require more water, wind-power desalination might become feasible in more areas. Also, as wind turbine technologies advance, electricity produced by wind power may be suitable for lower wind power classifications, making this integration feasible for a much larger area of Texas. The public’s expectations of paying little for water may not be met in the future as cities have to turn to more costly water sources due to decreasing existing supplies.

When considering implementation of a wind-powered brackish groundwater facility, sustainability must also be considered. Excessive aquifer pumping depletes exhaustible groundwater resources and can lead to land subsidence. Further analysis needs to be conducted to ensure brackish groundwater is extracted at a sustainable rate. Also, concentrate waste from reverse osmosis operations for inland locations can add challenges and costs. These challenges and costs should be further examined prior to implementation of a desalination facility.

**NOMENCLATURE**

<table>
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<th>Symbol</th>
<th>Description</th>
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<tr>
<td>$c_{wt}$</td>
<td>Cost of wind turbine, $</td>
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<tr>
<td>$P_{wt}$</td>
<td>Power of wind turbine, W</td>
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<tr>
<td>$c_{tr}$</td>
<td>Cost of wind power transmission, $</td>
</tr>
<tr>
<td>$c_{wop&amp;M}$</td>
<td>Cost of wind power operations and maintenance, $/d</td>
</tr>
<tr>
<td>$c_{RO}$</td>
<td>Cost of reverse osmosis equipment, $</td>
</tr>
<tr>
<td>$q$</td>
<td>Water flow rate, m³/s</td>
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<tr>
<td>$c_{gw}$</td>
<td>Cost of brackish groundwater well, $</td>
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<tr>
<td>$z$</td>
<td>Depth to aquifer, m</td>
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<tr>
<td>$c_{wd}$</td>
<td>Cost of water distribution pipeline, $</td>
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<tr>
<td>$L$</td>
<td>Pipe length, m</td>
</tr>
<tr>
<td>$D$</td>
<td>Pipe diameter, m</td>
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<tr>
<td>$c_{RO&amp;O&amp;M}$</td>
<td>Cost of reverse osmosis operations and maintenance, $/d</td>
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<tr>
<td>$c_{BGW}$</td>
<td>Cost of brackish groundwater, $/d</td>
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<tr>
<td>$TC$</td>
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</tr>
<tr>
<td>$t$</td>
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<td>$TR$</td>
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<td>$η_{RO}$</td>
<td>Reverse osmosis system recovery</td>
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<td>$P_f$</td>
<td>Power requirements for pumping, W</td>
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<td>$P_D$</td>
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<tr>
<td>$ρ$</td>
<td>Density of water, kg/m³</td>
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<td>$g$</td>
<td>Acceleration due to gravity, m/s²</td>
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<td>$CF_W$</td>
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<td>$f$</td>
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<td>$E_w(TDS)$</td>
<td>Energy for brackish groundwater desalination, kWh/m³</td>
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<td>LCOE</td>
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<td>LCOW</td>
<td>Levelized cost of water, $/m³</td>
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<td>CAPEX</td>
<td>Capital expenditures</td>
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<td>$d$</td>
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**ACKNOWLEDGEMENTS**

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**REFERENCES**


