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Article

Implementation of Brackish Groundwater Desalination Using Wind-Generated Electricity: A Case Study of the Energy-Water Nexus in Texas

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Abstract: Growing populations and periodic drought conditions have exacerbated water stress in many areas worldwide. In response, some municipalities have considered desalination of saline water as a freshwater supply. Unfortunately, desalination requires a sizeable energy investment. However, renewable energy technologies can be paired with desalination to mitigate concern over the environmental impacts of increased energy use. At the same time, desalination can be operated in an intermittent way to match the variable availability of renewable resources. Integrating wind power and brackish groundwater desalination generates a high-value product (drinking water) from low-value resources (saline water and wind power without storage). This paper presents a geographically-resolved performance and economic method that estimates the energy requirements and profitability of an integrated wind-powered reverse osmosis facility treating brackish groundwater. It is based on a model that incorporates prevailing natural and market conditions such as average wind speeds, total dissolved solids content, brackish well depth, desalination treatment capacity, capital and operation costs of wind and desalination facilities, brine disposal costs, and electricity and water prices into its calculation. The model is illustrated using conditions in Texas (where there are counties with significant co-location of wind and brackish water resources). Results from this case study indicate that integrating wind turbines and brackish water reverse osmosis (BWRO) systems is economically favorable in a few municipal locations in West Texas.

Keywords: brackish groundwater; reverse osmosis; desalination; wind power; economics; policy

1. Introduction

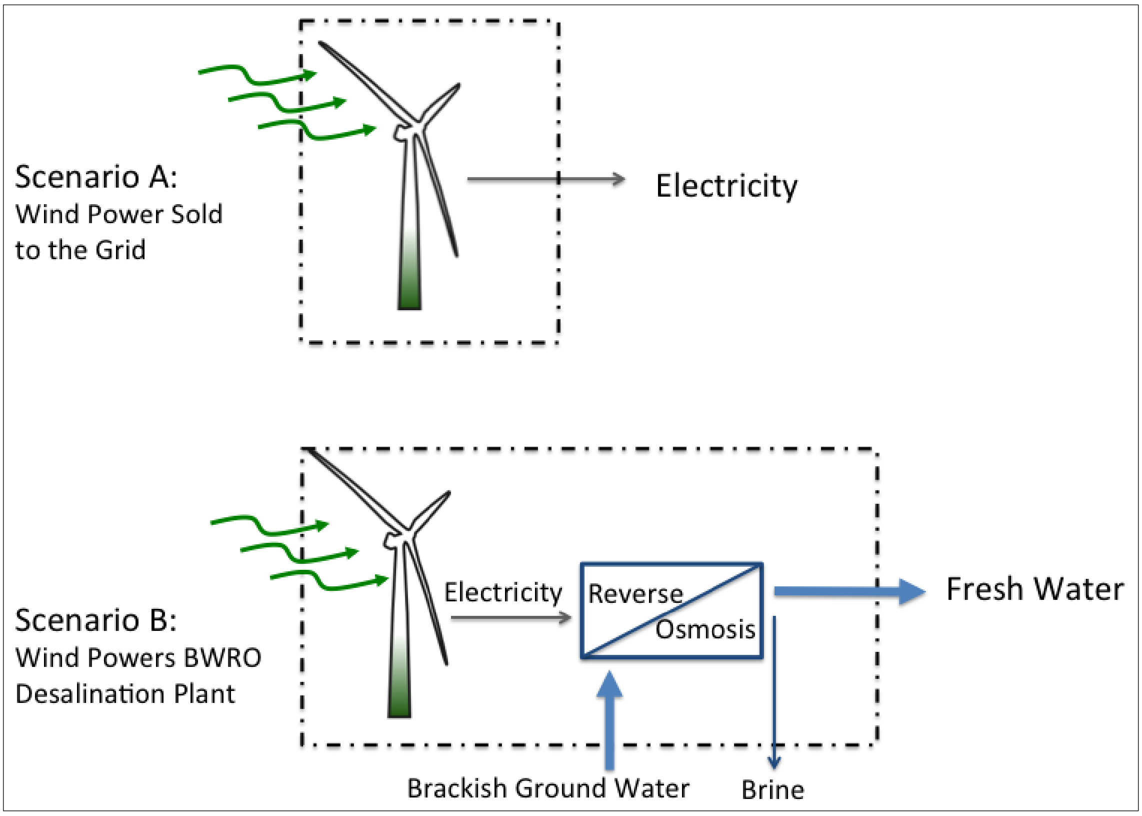
Many areas of the United States are at high risk for water shortages, if they are not already facing water constraints due to increasing demands for water coupled with decreasing water supplies and increases in the frequency and severity of droughts. Alternative water sources are oftentimes located further from the consumer or are of lower quality, requiring additional energy inputs for transportation or treatment. For example, desalination of brackish water using reverse osmosis, the most common desalination membrane treatment process, consumes approximately 10 times as much energy per unit of water as traditional surface water treatment [1]. Thus, as cities begin to pursue alternative water supplies for drinking water, it is reasonable to expect that additional energy for water collection, conveyance, treatment, and disinfection will be needed in the water sector, which is potentially incongruous to typical municipal goals of reducing energy consumption and carbon emissions.

A seemingly independent issue faced by resource planners, grid managers, and policy makers is the variability associated with large-scale integration of wind power into the electricity grid. Wind resources are subject to somewhat predictable diurnal and seasonal variations as well as other intermittency that is more difficult to forecast. Furthermore, continental wind is often out of phase with demand; when electricity demand is highest in the afternoons, wind is at its weakest and when electricity demand is at its lowest in the night, wind reaches its peak. Similarly, continental wind resources are weakest in the summer, when electricity demands are highest, and strongest in the winter or shoulder months, when electricity demands are typically lower. Another challenge faced by wind implementations is the requirement of large, expensive electricity transmission infrastructure that is time intensive and expensive to construct, as wind farms are often located far from populations. Additionally, high capital costs of wind turbines and the depressed electricity market clearing prices during wind resource output times can cause low or negative profitability for wind farms. The potential expiration of the production tax credit could further limit profitability of wind farms. Planners and policy makers have claimed that energy storage technologies must be developed to offset these limitations [2].

One possible solution to these two independent issues is the utilization of wind-generated electricity for desalination of brackish groundwater. This integration presents an opportunity to transform low-value products (brackish groundwater and intermittent electricity) into a high-value product (treated drinking water). The high energy requirement of the desalination process is a major limitation of this technology; therefore, coupling with renewable energy sources, such as wind, allows for freshwater production without increasing dependence on carbon-emitting fuel sources. Furthermore, desalination plants can be ramped up and down or operated during off-peak hours when wind is available and demand on the grid is low. However, this solution faces challenges, as implementation of a brackish groundwater desalination project using wind-generated electricity requires economic feasibility and the geographic availability of the two resources in close proximity to each other.

To understand the economic feasibility of integrated facility, the potential annual profitability of an integrated wind and brackish water reverse osmosis (BWRO) desalination plant from water sales (Scenario B in Figure 1) is compared to the potential annual profitability of a traditional wind project from electricity sold to the grid (Scenario A in Figure 1) for a range in project parameters. This research develops a methodology for evaluating the (1) energetic performance; (2) economic feasibility; and (3) geographic feasibility of implementing a brackish groundwater desalination plant using wind-generated electricity. The method is demonstrated for Texas, which is a suitable testbed for this analysis as both wind and brackish groundwater resources are abundant in the state. Various project parameters and a range of capital and operation costs of wind and desalination technologies are used to examine the energy balance and potential annual profitability for an integrated wind and desalination plant. Those assessments are compared to a stand-alone wind power project. The availability of wind and brackish groundwater resources and profitability of an integrated facility is modeled using geographic information systems tools to illustrate areas where implementation of a wind-powered desalination project is economically and technologically feasible.

Figure 1. The two configurations are analyzed based on the methodology presented. Scenario A (**top panel**) shows conventional wind generation for sale to the grid. Scenario B (**bottom panel**) shows wind generation integrated with a brackish groundwater desalination facility to produce freshwater.

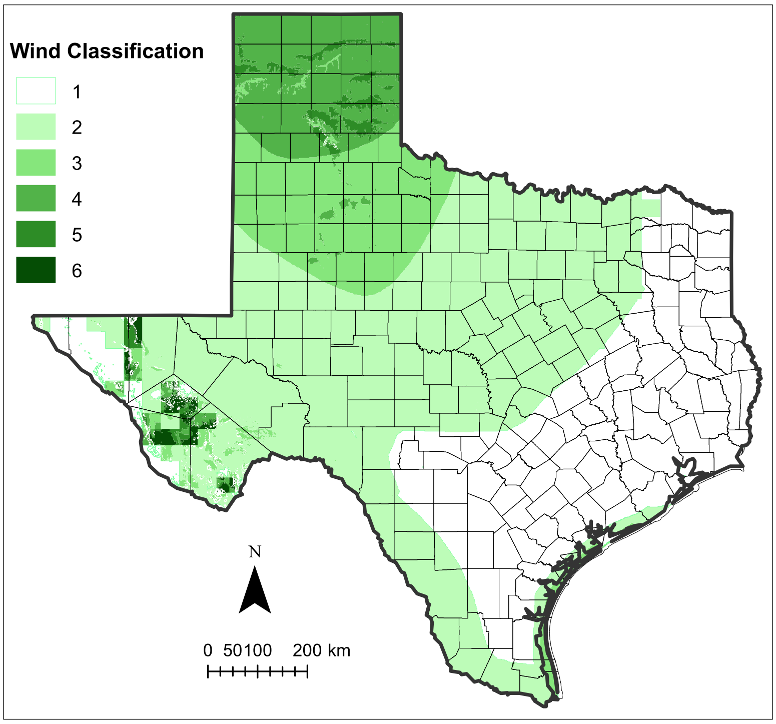


2. Background

2.1. Wind Power

With a push toward renewable electricity standards and existing production tax credits for wind-generated electricity, the last decade has witnessed substantial growth in wind power. Wind power comprised 43% of the electricity generating capacity additions in the United States in 2012 [3]. Of the 60,000 MW of installed wind generation capacity in the United States at the end of 2012, Texas currently leads the nation with 12,200 MW [4]. Texas is also the lowest-cost region for installed projects [3]. Typically, a wind class of 3 or greater is considered to be profitable for generating energy with large wind turbines at utility scale. As shown in Figure 2, wind resources are prevalent in the panhandle region of Texas [5]. Furthermore, if electricity 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 suitable for wind power generation.

Figure 2. Wind classification considered to be suitable for utility-scale wind exists in the panhandle regions of Texas [5].



Although wind resources are abundant, the inherent variability inhibits the growth of this technology. The intermittent nature of this resource does not allow operators to dispatch wind power to meet load as they can with conventional baseload power plants. Furthermore, continental wind farms have a diurnal and seasonal variability that is typically mismatched with demand. Also, wind power projects are constrained to areas with adequate wind speeds, which are often located at a distance from load centers. Curtailment of wind output due to transmission inadequacy has become a significant problem, specifically in Texas despite recent growth in transmission development [3]. Within the Electric Reliability Council of Texas, 8.5% of potential wind energy generation was curtailed in 2011 [3].

Energy storage technologies provide opportunities to shift electricity from periods of low demand to those of higher demand or damp out fluctuations in output. Beyond direct energy storage, one option to mitigate grid-wide challenges is to dedicate wind power to energy-intensive, high-value processes that can be operated intermittently, such as wind-powered desalination. Thus, desalination coupled with wind might serve as an alternative for storage.

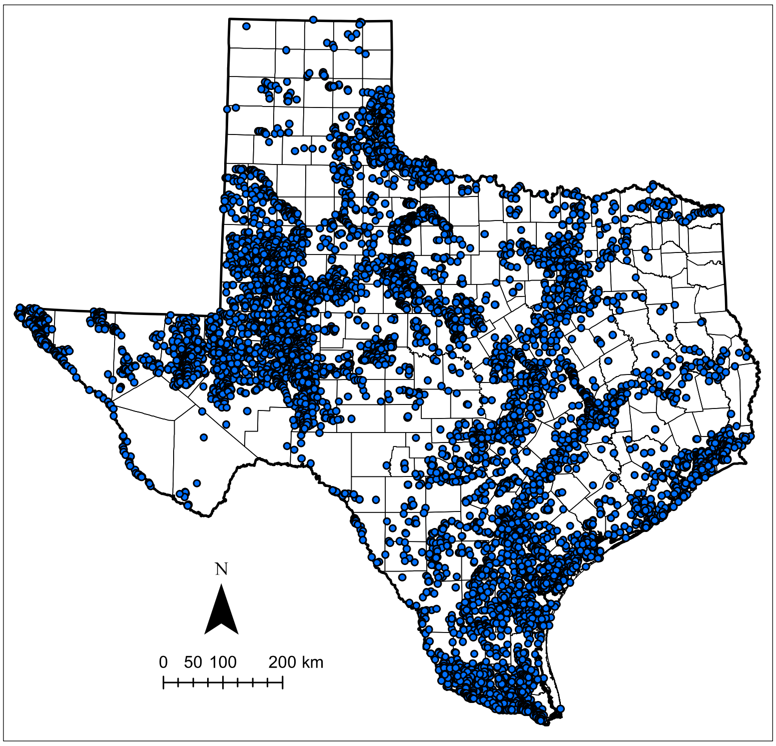
2.2. Desalination

Desalination is used to treat saline water (total dissolved solids (TDS) concentration greater than 10,000 mg/L) and brackish water (TDS between 1000 and 10,000 mg/L). The Texas Commission on Environmental Quality has set a primary standard concentration for TDS of 500 mg/L and a secondary standard of 1000 mg/L for public use [6]. Generally, there is little competition for access to brackish groundwater as it is unusable for agricultural irrigation due to high levels of TDS. The utility of desalination is generally recognized as being limited by its costs, energy requirements, and geography. Estimated worldwide capacity totaled only 22 billion m^3 per year (15.8 billion gal/day), or 0.5% of global freshwater use, in 2010 [7]. However, improvements in desalination technologies coupled with increasing demand for water supply has enabled significant growth in interest and implementation of desalination projects.

The Texas Water Development Board projects a need of 8 billion m^3 per year in new water supplies by 2060 for the state to meet the 22% growth in demand and 10% decrease in existing water supply. The state water planners have identified water management strategies to meet these significant water needs, including increasing groundwater desalination to over 220 million m^3 per year for the state [6]. Brackish groundwater is prevalent in much of Texas, as there are approximately 10,000 wells with a range in TDS of 1000 to 10,000 mg/L and in depth of zero to 2225 m, as demonstrated in Figure 3 [8]. The total estimated volume of brackish groundwater in Texas aquifers is over 3.1 trillion m^3 [9]. There are 44 brackish water desalination facilities in Texas with a total capacity of 166 million m^3 per year (120 million gallons per day) [10]. Established and reliable desalination technologies include reverse osmosis (RO), multi stage flash, multi effect distillation, and electrodialysis [11]. Of the 44 brackish water desalination facilities in Texas, 42 use a reverse osmosis (RO) process [10]. RO is considered for this analysis, as it is the most common, energy-efficient, and economical process. The RO desalination process involves separating the saline water (feed) into two streams: low-salinity product water (permeate) and very saline reject water (brine or concentrate). Recovery from RO treatment of brackish water ranges from 50% to 90%, depending on water quality and operating parameters [1].

Implementation of desalination facilities face challenges due to the expensive specialized infrastructure required and the high-energy requirements compared to conventional surface freshwater treatment. Brackish groundwater desalination for inland locations has the additional challenge of concentrate disposal. Current options for concentrate disposal include sewer or surface water discharge after wastewater treatment processes, land application, deep well injection, evaporation ponds, and zero liquid discharge [12]. The most appropriate concentrate disposal method depends on specific site conditions and local regulations. 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.

Figure 3. Brackish groundwater wells are prevalent throughout the state of Texas [8]. Each blue dot indicates a brackish well.



2.3. Integrated Wind and Desalination Technology

Wind-powered desalination combines RO with wind power with the intent of producing 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). While this approach seems promising, to the authors' knowledge, no methodology has been published that allows for the rigorous calculation of economic tradeoffs as a function of different technical factors. This paper seeks to fill that knowledge gap by analyzing the economic feasibility of this integration with the intent of aiding planners and decision-makers who might contemplate this configuration to solve electricity and water challenges. For this analysis, the wind power and desalination systems are integrated and co-located but are considered to operate as separate facilities.

Wind-generated electricity and desalination have been installed in other locations and there is a small body of prior published analyses. Previous research by Veza *et al*. demonstrated the feasibility of using off-grid wind-generated electricity to power electrodialysis desalination [13]. Others have reported successful implementation of desalination processes using renewable energy, such as wind and photovoltaic solar [14–18]. The wind-powered, Perth Seawater RO Plant in Australia opened in November 2006; it uses an 80-MW wind farm, consisting of 48 wind turbines, to power the desalination process and yields approximately 9.4 m^3 of drinkable water every minute (3.6 million gal/day) [19]. This project demonstrates the technical feasibility of the integration of wind power and desalination. Additionally, the City of Seminole, Texas has partnered with Texas Water Development Board and

Texas Tech University to provide additional municipal water supply by desalinating brackish water from the Dockum Aquifer in Gaines County using a grid-connected 50 kW wind turbine [20].

Desalination facilities directly connected to a renewable energy power supply must also consider the inherent intermittency of the energy resources. Membranes are designed to operate under constant pressure to maintain performance and avoid damage. Operation of wind-powered membrane systems under pressure fluctuations has been documented and pilot studies have demonstrated that, over short periods of time, membranes can be operated in a variable manner without deteriorating. The long term consequences of cycling membrane systems on and off have not been determined, yet some facilities have successfully operated using variable flow desalination equipment tied to wind turbines without batteries [15,16] and wind-photovoltaic hybrid power supplies [17,18].

3. Methodology

The utilization of electricity generated from a wind turbine to produce fresh water with a brackish water reverse osmosis (BWRO) desalination plant is analyzed. The methodology has three components: evaluation of the (1) energetic performance; (2) economic feasibility; and (3) geographic feasibility of implementing an integrated facility. The method is demonstrated for a range of characteristics using Texas as a testbed.

3.1. Energetic Performance Analysis

The power requirements of the BWRO desalination facility (P, in kW) are estimated to determine appropriate desalination and wind turbine capacities and generations. Power is required for pumping water from the aquifer and in pipelines (P_P, in kW) and for brackish groundwater desalination (P_D, in kW), as defined in Equation (1):

$$P = P_P + P_D \ \ (kW) \tag{1}$$

The calculation of P_P is developed considering the Darcy-Weisbach equation for head loss in pipes and depends on the flow rate into the facility (q, in units of cubic meters per second, see Equation (3)), the desalination capacity factor (CF_D, a dimensionless ratio), depth to aquifer (z, in meters), the distribution pipe length (l, in meters), and other standard parameters (summarized in Table 1), as defined in Equation (2):

$$P_P = \frac{\rho g q}{1000 \eta_P CF_D}\left(z[m] + \frac{\left(\frac{4q}{\pi (d)^2}\right)^2}{2g}\frac{f}{d}(z+l) \right) \ \ (kW) \tag{2}$$

The flow rate into the facility (q, in cubic meters per second) depends on the desired daily product water generation (G_D, in cubic meters of treated water per day) and the BWRO recovery rate (R_D), which is the ratio of product water flow to incoming flow, as defined in Equation (3) (including a conversion from day to seconds):

$$q = \frac{1}{86{,}400} \times \frac{G_D}{R_D} \ \ \left(\frac{m^3}{s}\right) \tag{3}$$

Table 1. Standard parameters are considered in the calculation of the power requirements for pumping.

Factor	Description	Units	Value
ρ	Density of water	kg/m^3	1000
g	Acceleration due to gravity	m/s^2	9.81
η_P	Pump efficiency	-	0.65
d	Pipe diameter	m	0.30
f	Friction factor	-	0.0162

The capacity factor, CF_D, is the dimensionless ratio of the actual output of the facility over a period of time to the potential output of the facility operating at full capacity. To account for maintenance interruptions, it is assumed for the analysis in this manuscript that the desalination facility is operational 95% of the time electricity is provided, however future work could make that an operational variable using these equations. The power requirement for desalination (P_D, in units of kW) is a function of q, CF_D, and the energy intensity of desalination (EI_D, in units of kWh per cubic meter), as defined in Equation (4):

$$P_D = \frac{3600\ EI_D q}{CF_D}\ (kW) \tag{4}$$

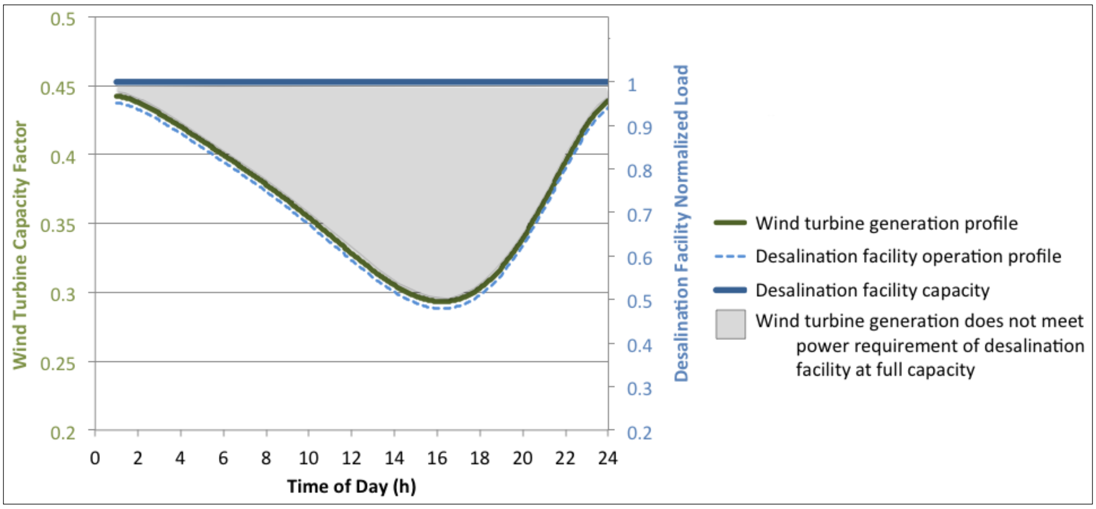
EI_D is function of the TDS of the source water and the desalination technology. The national average electricity use for brackish groundwater treatment is 1.0 to 2.6 kWh/m^3 [21,22]. A range in BWRO project parameters—R_D, z, l, and EI_D—from favorable (requiring less power) to unfavorable (requiring more power) are considered in the calculation of the project capacities and generations, as given in Table 2.

Table 2. Ranges in brackish water reverse osmosis (BWRO) project parameters are considered in the calculation of the project capacities and generations.

Factor	Project Parameters	Units	Favorable	Average	Unfavorable
R_D	BWRO recovery	-	0.9	0.8	0.7
z	Depth to aquifer	m	50	275	500
l	Distribution pipe length	m	500	5250	10,000
EI_D	Energy intensity of desalination	kWh/m^3	1.03	1.8	2.56
CF_{WT}	Wind turbine capacity factor	-	0.45	0.35	0.25

The energy supplied to the BWRO desalination facility from the wind turbine will not be constant due to the inherent variability of wind resources. To accommodate for this variable energy supply and meet the desired generation of treated water, either the BWRO desalination facility must be sized to meet peak wind output or the wind turbine must be sized to meet constant demand of the BWRO desalination facility at low wind output. The analysis presented assumes the BWRO desalination facility and wind turbine capacities are sized to meet peak of average generation of the wind turbine, as shown in Figure 4. The wind turbine capacity factor is the ratio of actual output over a period of time to its potential output if it were possible for it to operate at full nameplate capacity indefinitely. For example, on an average day, the peak output ($CF_{WT,Peak}$) is approximately 45% of the installed capacity, and the average output ($CF_{WT,Avg}$) is approximately 35% of the installed capacity [23]. The BWRO is sized based on the peak output. The peak output is considered to vary with the favorability of the wind resource. During a typical day, the wind turbines performs below the typical peak for some parts of the day, in which case there will be less generation of electricity than what the BWRO consumes at full operation. In those cases, the BWRO facility would reduce operation. The area shaded in light gray in Figure 4 indicates the desalination facility is operating at less than full capacity and consumes all electricity generated by the wind turbine for a typical day.

Figure 4. The economic feasibility analysis and the geographic feasibility analysis presented assume the BWRO desalination facility and wind turbine capacities are sized so that they align at the wind turbine's average peak generation. Consequently, there are many hours (shown by the shaded area) when the wind turbine does not meet the power requirements of the desalination facility operating at full capacity. Furthermore, if the wind turbine exceeds its average peak, then it will be generating excess electricity beyond what the desalination facility needs.



The economic and geographic feasibility models evaluate profitability considering annual production. The capacity of the wind turbine considered (C_{WT}, in units of kW) is determined based on the power requirement of the desalination facility for desired generation (P, in units of kW) and the peak of the average wind turbine capacity factor daily profile ($CF_{WT,Peak}$, a dimensionless ratio), as in Equation (5):

$$C_{WT} = \frac{P}{CF_{WT,Peak}} \ (kW) \tag{5}$$

The capacity of the BWRO desalination facility considered (C_D, in units of cubic meters per day) is determined based on the desired daily product water generation (G_D, in units of cubic meters per day), the desalination recovery factor (R_D, a dimensionless ratio), and the average wind turbine capacity factor ($CF_{WT,Avg}$, a dimensionless ratio), as in Equation (6):

$$C_D = \frac{\frac{G_D}{R_D}}{CF_{WT,Avg}} \left(\frac{m^3}{day}\right) \tag{6}$$

The annual electricity generation of the wind turbine ($G_{WT,a}$, in units of kWh per year) is determined based on C_{WT} and $CF_{WT,Avg}$, as in Equation (7) (including a conversion from hours to years):

$$G_{WT,a} = 8766 \times C_{WT} \times CF_{WT,Avg} \left(\frac{kWh}{year}\right) \tag{7}$$

For the analyses presented, the desired daily product water generation (G_D) is considered as 3,800 m^3 per day (1,000,000 gallons per day), enough water for 7600 people each using 0.5 m^3 (140 gallons) per person per day, a water conservation metric in Texas [24]. This production provides an annual product water generation ($G_{D,a}$) of 1,100,000 m^3/year considering an average recovery of 80%. A range of the wind turbine capacity factor is considered in the calculation of the project capacities and generations, as shown in Table 2. Other factors could be used to represent different geographic locations or to examine the effects of a wider range of performance.

The influence of ranges in project parameters on the power requirements of the BWRO desalination facility are demonstrated based on the energetic methodology presented. Then appropriate desalination and wind turbine capacities and generation values are used to evaluate the economic and geographic feasibility.

3.2. Economic Feasibility Analysis

To understand the economic feasibility of integrated wind power and brackish groundwater desalination, a method to estimate profitability based on energetic requirements and cost factors was developed using brackish groundwater well and BWRO characteristic data, wind resource and turbine characteristic data, capital and operational cost estimates of BWRO and wind facilities, and water and electricity prices. To illustrate the methodology, the potential annual profitability of an integrated wind and BWRO desalination plant from water sales (Scenario B in Figure 1) is compared to the potential annual profitability of a traditional wind project from electricity sold to the grid (Scenario A in Figure 1) for a range in project parameters. As described before, the generation and capacity values considered for Scenario B are based on the assumption that the BWRO desalination facility and wind turbine capacities are sized to meet peak of average generation of the wind turbine. The capacity of the wind turbine considered for Scenario A is modeled equivalent to the capacity of the wind turbine of Scenario B.

The profitability of the scenarios is determined as the revenue less the costs. The revenue of Scenario A is based on the sale of electricity to the grid and the renewable energy production tax credit (PTC) of \$0.023 per kWh generated, while the revenue of Scenario B is based on the sale of treated water to a utility [21]. Costs are comprised of both capital (*CAPEX*, in units of \$ per kW of built capacity) and operational (*OPEX*, in units of \$ per kWh generated) expenses. Scenario B has a greater set of costs as both the wind turbine facility and the BWRO desalination facility must be built and maintained. The profitability of Scenario A (Pr_A, in units of \$ per year) is determined based on the price of electricity (P_e, in units of \$ per kWh generated), the PTC, the wind turbine capacity (C_{WT}, in kW), the annual electricity generation ($G_{WT,a}$, in units of kWh per year), the capital and operational costs of the wind turbine, and the annuity factor (A, in years), as defined in Equation (8):

$$\mathrm{Pr_A} = \left[\{\mathrm{P_e} + \mathrm{PTC}\} \times \mathrm{G_{WT,a}}\right] - \left[\frac{\mathrm{CAPEX_{WT}} \times \mathrm{C_{WT}}}{\mathrm{A}}\right] - \left[\mathrm{OPEX_{WT}} \times \mathrm{G_{WT,a}}\right] \left(\frac{\$}{\mathrm{year}}\right) \tag{8}$$

Similarly, the profitability of Scenario B (Pr_B, in units of \$ per year) is determined based on the price of water (P_W, in units of \$ per m^3 of produced treated water), the desalination capacity (C_D, in units of cubic meters per day of built capacity), the annual water production ($G_{D,a}$, in units of cubic meters per year of produced treated water), the capital and operational costs of the wind turbine and the desalination facility, and *A*, as defined in Equation (9):

$$\mathrm{Pr_B} = \left[\mathrm{P_w} \times \mathrm{G_{D,a}}\right] - \left[\frac{\mathrm{CAPEX_D} \times C_D + \mathrm{CAPEX_{WT}} \times \mathrm{C_{WT}}}{\mathrm{A}}\right] - \left[\mathrm{OPEX_D} \times \mathrm{G_{D,a}} + \mathrm{OPEX_{WT}} \times \mathrm{G_{WT,a}}\right] \left(\frac{\$}{\mathrm{year}}\right) \quad (9)$$

The PTC is not considered for the integrated facility as the wind turbine is considered co-located with the desalination facility, and therefore behind the electricity meter and the PTC is expected to end. However, profitability of Scenario B would be greater if the facility qualified for the credit. The upfront capital costs are amortized as annual payments using the annuity factor (*A*, in years) based on the life of the project (*n*, in years) and a nominal interest rate (*i*), as defined in Equation (10):

$$\mathrm{A} = \frac{1 - (1 + \mathrm{i})^{-\mathrm{n}}}{\mathrm{i}} \ (\mathrm{year}) \quad (10)$$

For this analysis, *i* of 5% and *n* of 20 years is considered, producing an *A* of 12.5. The annual profitability estimates are determined based on capital and operational costs and on electricity and water prices, for Scenario A and Scenario B, respectively. The potential revenue for treated water prices is highly variable, as the market for drinking water in Texas tends to be local, monopoly-controlled, and regulated. Municipal retail prices range from \$0.20 to \$2.20 per m^3 in Texas [24]. As water supply needs grow and available sources decline, the value of water might increase significantly.

In this analysis, profitability of Scenario B is determined for a range in water prices of \$0.20 to \$2.80 per m^3 of product water. This range is considered because prices will likely increase in the near future due to decreases in water supply from climate change and increases in demand from population and economic growth. To compare the integrated facility with a stand-alone wind turbine scenario, electricity prices must also be considered. Profitability of Scenario A is determined based on a range in total electricity prices of \$0.02 to \$0.15 per kWh generated, which are typical wholesale rates for the clearing price of electricity in ERCOT throughout the year. (Note: while \$0.15/kWh is not unusual during peak times in the summer, it much higher than the annual average clearing price, which is closer to \$0.025/kWh [22].) A subsequent analysis could incorporate price functions to account for variation by location and time.

The capital and operational costs considered in the annual profitability calculations are reported in literature, as summarized in Table 3. Cost values are adjusted to 2012 dollars using the Consumer Price Index (CPI) from the United States Bureau of Labor Statistics [25]. Constructing wind turbines and RO facilities are capital intensive and the ranges in costs found in literature are wide due to uncertainty in materials availability, technology, operations, and financing options. To produce conservative results, high estimates were taken from literature to develop the range considered in this analysis.

The economic methodology presented was developed to generate conclusions of the economic feasibility of integrated wind power and brackish groundwater desalination. The results are depicted for ranges in brackish groundwater well and BWRO characteristic values, wind resource and turbine characteristic values, capital and operational cost values of BWRO and wind facilities, and water and electricity prices.

Table 3. Reported values for fixed and variable costs associated with brackish groundwater desalination using wind power in Texas are considered.

Expense	Units	Reported Costs			Source
		Low	Average	High	
Wind Turbine Project Capital	\$/kW	1500	2250	3000	[3]
Wind Turbine Project Operational	\$/MWh	7	11	15	[3]
Reverse Osmosis Facility Capital	\$/m^3/day	300	400	500	[8,26,27]
Well Field and Delivery Capital	\$/m^3/day	250	350	450	[8,26,27]
Delivery to Municipal Line Capital	\$/m^3/day	50	75	100	[8,26,27]
Reverse Osmosis Project Operational	\$/m^3	0.08	0.14	0.19	[26,27]
Concentrate Discharge Capital	\$/m^3/day	250	500	750	[11,28]
Concentrate Discharge Operational	\$/m^3	0.01	0.04	0.06	[11,28]

3.3. Geographic Feasibility Analysis

In addition to the economic analysis, the geographic feasibility is considered. For this analysis, the availability of resources and profitability are modeled using geographic information systems (GIS) tools to illustrate areas in Texas where implementation of this integration might be economically feasible based on the economic methodology presented above. Two geographic datasets are used to perform this analysis:

- Brackish groundwater wells: The dataset from the Texas Water Development Board (TWDB) provides location, depth, and water quality of Texas brackish groundwater wells [8]. The dataset demonstrates the prevalence of brackish groundwater in Texas, as shown in Figure 3.
- Wind power classification: The dataset from the National Renewable Energy Laboratory (NREL) provides wind energy potential as a GIS raster file [5]. The dataset demonstrates the availability of wind resources with classifications of 3 or greater, as shown in Figure 2, which is generally considered the minimum threshold for profitably generating electricity with large wind turbines.

The wind turbine capacity requirement and electricity production value, determined by Equations (1)–(9), at each brackish groundwater well are modeled based on the depth to the water table and TDS provided by the TWDB dataset and the wind power classification provided by the NREL dataset. A range of wind turbine capacity factors of 0.25 to 0.45 is considered based on a linear function of the wind power classifications of 3 to 7 (CF_{WT} of 0.25 corresponds to wind power classification of 3, CF_{WT} of 0.35 corresponds to wind power classification of 5, CF_{WT} of 0.45 corresponds to wind power classification of 7) [3]. The energy intensity of desalination (EI_D) is modeled as a linear function of the TDS based on the national average range in electricity use for brackish groundwater desalination of 1.0 to 2.6 kWh/m^3 and the range of TDS values for brackish groundwater, as defined in Equation (11) [24,29]:

$$\mathrm{EI}_D = \frac{(2.6 - 1.0)(\mathrm{TDS} - 1000)}{(10{,}000 - 1000)} + 1.0 \quad \left(\frac{\mathrm{kWh}}{m^3}\right) \tag{11}$$

Prices of water of \$0.20, \$1.60, and \$2.80 per m^3 are considered. Based on this approach, areas of economical and geographic feasibility are identified and efforts to determine suitability of implementation based on water needs can be further considered.

4. Results

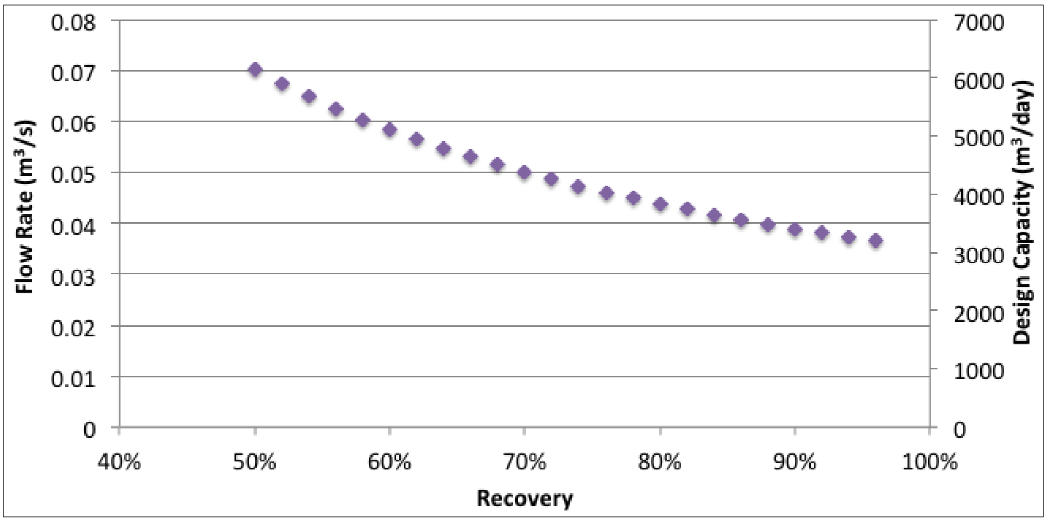
4.1. Energetic Analysis Results

Based on Equations (1) through (4) considering average recovery of 80% and the average of parameters indicative of Texas brackish groundwater wells (depth to aquifer of 275 m, pipe length of 5250 m, and energy intensity of desalination of 1.8 kWh/m^3), the power requirement of the desalination facility to produce 3000 m^3 per day (1,100,000 m^3/year) is 495 kW. This power requirement scales linearly with brackish groundwater parameters, as given in Table 4. The power requirement increases nonlinearly with desalination recovery. The range in flow rate (and design capacity) of the BWRO desalination facility is depicted for the range of recovery values of 50 to 96%, as shown in Figure 5.

Table 4. The power requirement of the desalination facility scales linearly with brackish groundwater parameters.

Increase in Power Requirement of Desalination Facility (kW)	
Per 1000 m length of pipe	0.68
Per 10 m depth to aquifer	6.97
Per 0.5 kWh/m^3 energy intensity	8.30

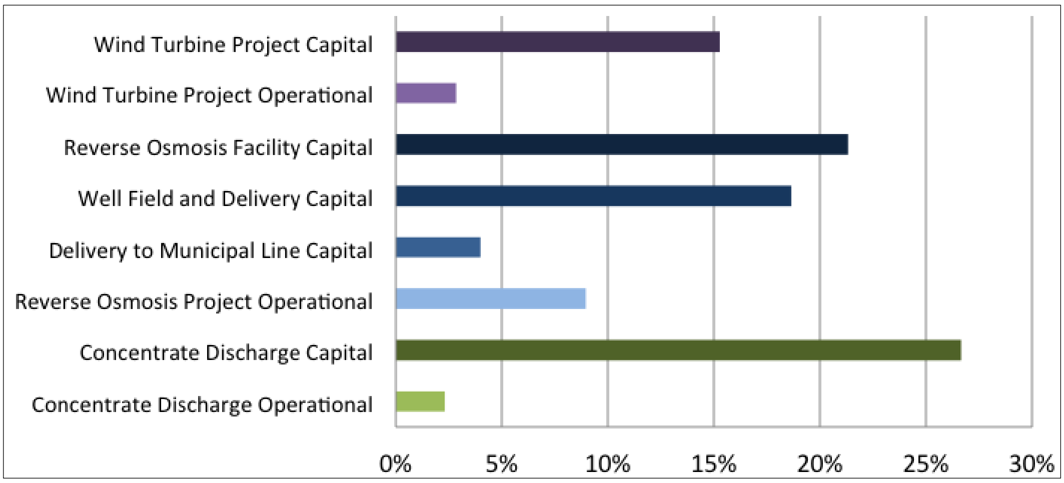
Figure 5. The recovery influences the flow rate into the facility and the necessary design capacity for a desired volume of water generation.



4.2. Economic Analysis Results

To summarize the capital and operational cost considerations and give a perspective on the influence of each project component, the weights of the equivalent annual costs for the integrated wind turbine and BWRO desalination facility are determined, as shown in Figure 6. These weights are calculated based on sizing of the BWRO desalination facility and wind turbine to operate at peak of average wind output. Average project parameters and capital and operational costs are considered. Due to sizing the desalination facility to operate at peak of average wind capacity, the capital expenses of the project will be considerably larger than necessary for the production level of water if the facility operated with a continuous energy source. The capital expenses associated with desalination are 71% of the total project expenses. Wind turbine project capital and operational expenses comprise only 18% of the integrated project expenses. Although the integrated facility, Scenario B, requires a much larger investment, the profit provided from water sales might exceed the profit provided from intermittent, off-peak electricity sales.

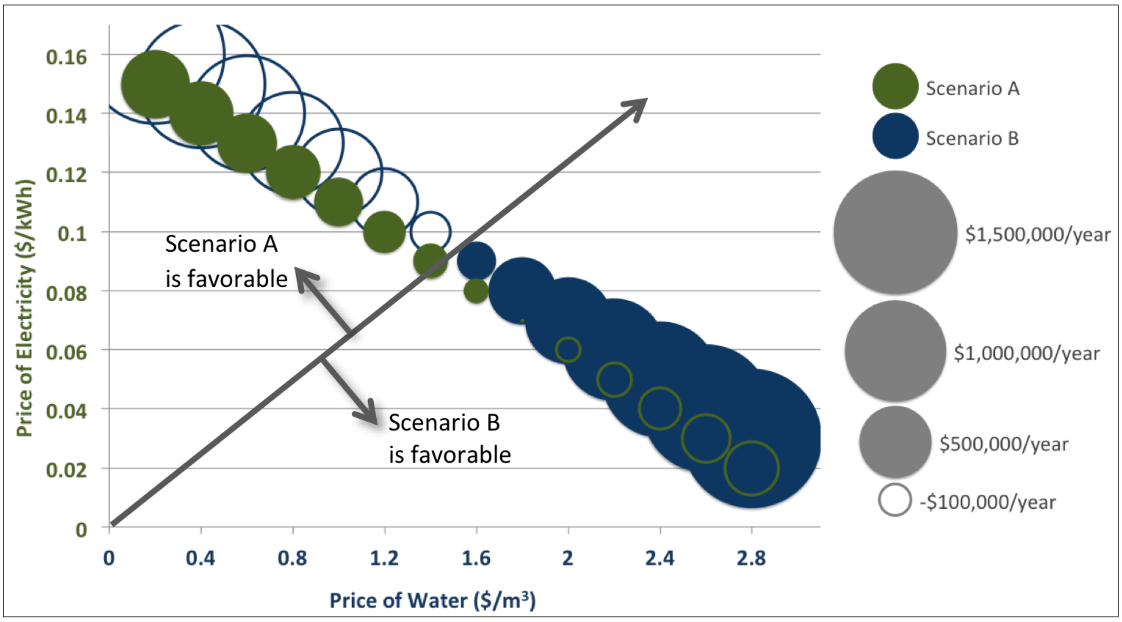
Figure 6. Allocations of the equivalent annual costs of project components of Scenario B demonstrate that the wind turbine project expenses comprise only 18% of total project expenses.



The potential annual profitability of an integrated wind and BWRO desalination plant (Scenario B in Figure 1) for a range of water prices is demonstrated with the potential annual profitability of a traditional wind project with electricity sold to the grid (Scenario A in Figure 1) for a range of electricity prices, as shown in Figure 7. These profitability values are determined based on the average of desalination project and wind turbine parameters, given in Table 2, and the average capital and operational costs, given in Table 3. The profitability of Scenario A is represented in green and the profitability of Scenario B is represented in blue. The size of the circles are proportional to the profitability, as demonstrated in the legend, with solid circles representative of positive values and rings representative of losses. Not surprisingly, Scenario A (selling the wind generation directly to the power market) is favorable when water prices are low and electricity prices are high. Scenario B (using the wind generated electricity to produce treated water) is favorable when electricity prices are low and water prices are moderate to high. Scenario A becomes profitable for water prices above approximately \$1.50 per m^3, which is within the range of current municipal retail prices of \$0.20 to \$2.20 per m^3 [24]. Scenario B becomes profitable for electricity prices above approximately \$0.07 per kWh, which is much higher than the annual average clearing price of approximately \$0.25 per kWh but not unusual during peak times in the summer. Profitability of Scenario A ranges from −\$220,000 to \$350,000 per year for a range of electricity prices of \$0.02 to \$0.15 per kWh generated. Profitability of

Scenario B ranges from −$1,400,000 to $1,400,000 per year for a range of water prices of $0.20 to $2.80 per m^3 produced.

Figure 7. Annual profitability based on the average of project parameters and costs demonstrate Scenario A is favorable when water prices are low and electricity prices are high and Scenario B is favorable when electricity prices are low and water prices are moderate to high. Profitability is normalized for an annual product water generation of 1,100,000 m^3/year.



Next, to consider the dependence of profitability on wind and desalination project parameters, annual profitability of Scenario A is determined for favorable and unfavorable wind conditions and the annual profitability of Scenario B is determined for favorable and unfavorable wind and desalination conditions, as shown in Figure 8. The project parameters considered are BWRO recovery, depth to aquifer, pipe length, energy intensity of desalination, and wind turbine capacity factor given in Table 2. Average capital and operational costs are considered for a range of electricity and water prices, given in Table 3. The profitability of Scenario B is normalized for an annual product water generation of 1,100,000 m^3/year. The profitability of Scenario A is normalized for an annual electricity generation of 1,800,000 kWh per year. This annual electricity generation is sufficient to power a desalination facility with an annual product water generation of 1,100,000 m^3/year at favorable desalination and wind conditions. As expected, Scenario A presents greater profitability for favorable wind parameters. Scenario B presents greater profitability for favorable desalination project parameters and favorable wind project parameters. An annual profitability of $700,000 is shown for Scenario A based on favorable wind conditions and a high electricity price of $0.15 per kWh generated for a project of wind turbine capacity based on unfavorable desalination conditions. An annual profitability of $1,880,000 is shown for Scenario B based on favorable desalination conditions, favorable wind conditions, and a high water price of $2.80 per m^3 produced.

The profitability of Scenario A and Scenario B is considered for low, average, and high capital and operational costs, given in Table 3, for a range of electricity and water prices, as shown in Figure 9.

Average desalination project and wind turbine parameters are considered, given in Table 2. As expected, profitability is greatest for low capital and operational costs and high prices. The profitability of Scenario B is more sensitive to the variation of capital and operational costs because the integrated facility requires a much larger investment.

Figure 8. Wind and desalination project parameters influence the annual profitability of Scenario A and of Scenario B. Scenario B is most profitable when water prices are high and conditions are favorable. Scenario A is most profitable when electricity prices are high and wind conditions are favorable.

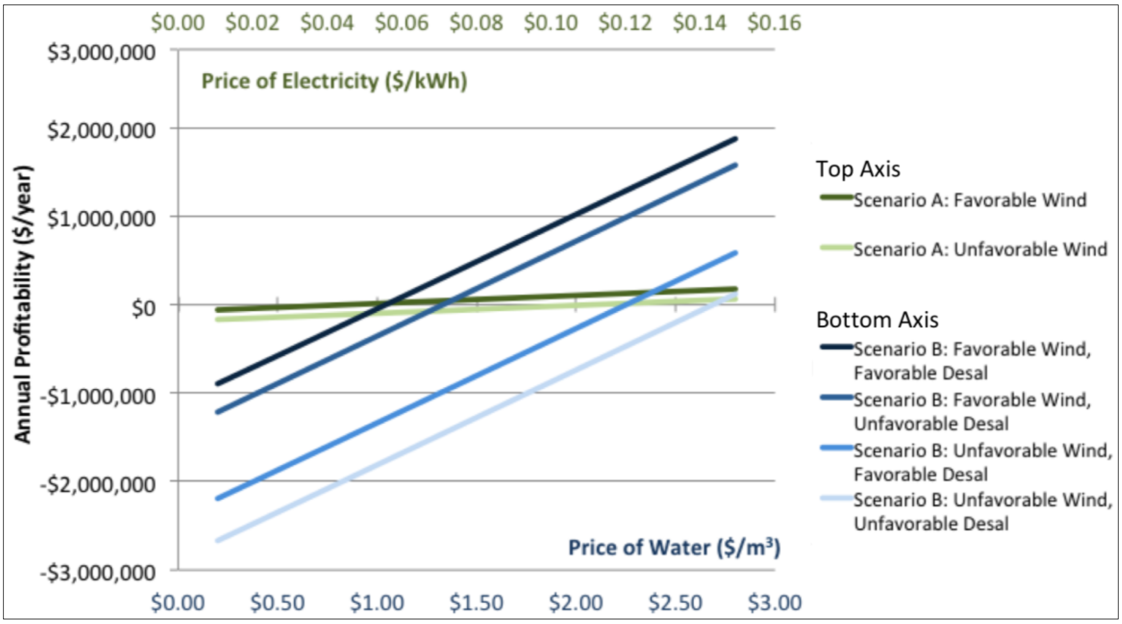
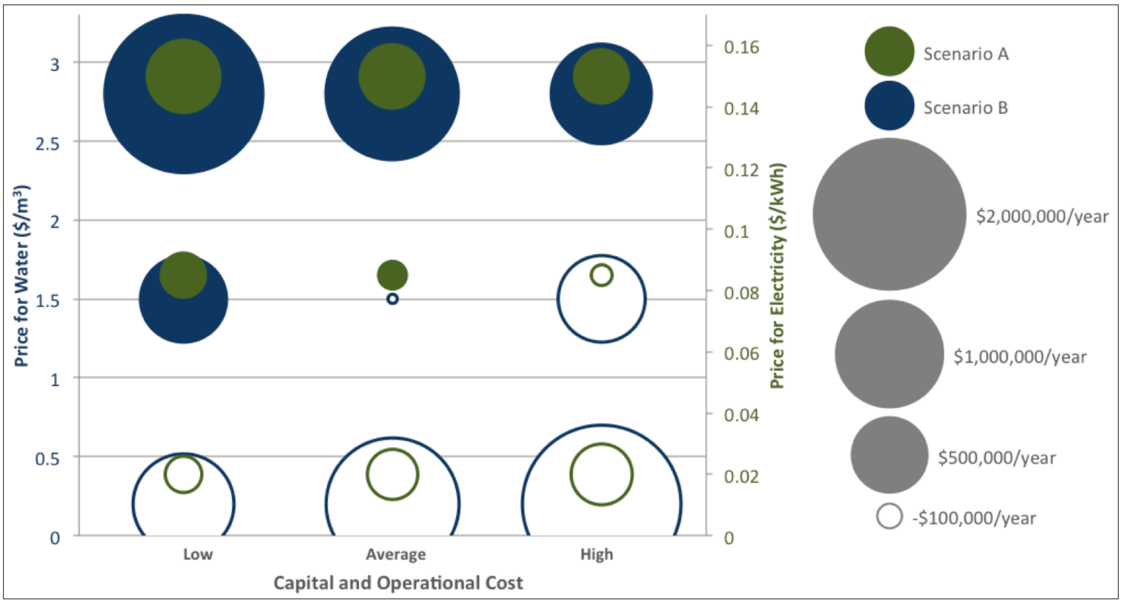


Figure 9. Wind and desalination projects require large capital and operational investments. Profitability is greatest for low costs and high prices. Profitability is normalized for an annual product water generation of 1,100,000 m^3/year.



These results demonstrate the potential economic feasibility of implementation of an integrated wind power and BWRO desalination facility to produce a higher value product. Although Scenario B requires a much larger investments in capital and operational components for the desalination technology in addition to the wind technology, the higher revenue from water prices creates greater potential profitability than for Scenario A with lower revenue from electricity prices. It also introduces risk of greater financial losses under unfavorable conditions, but presumably developers would not design and build such an expensive system if prevailing conditions are unfavorable.

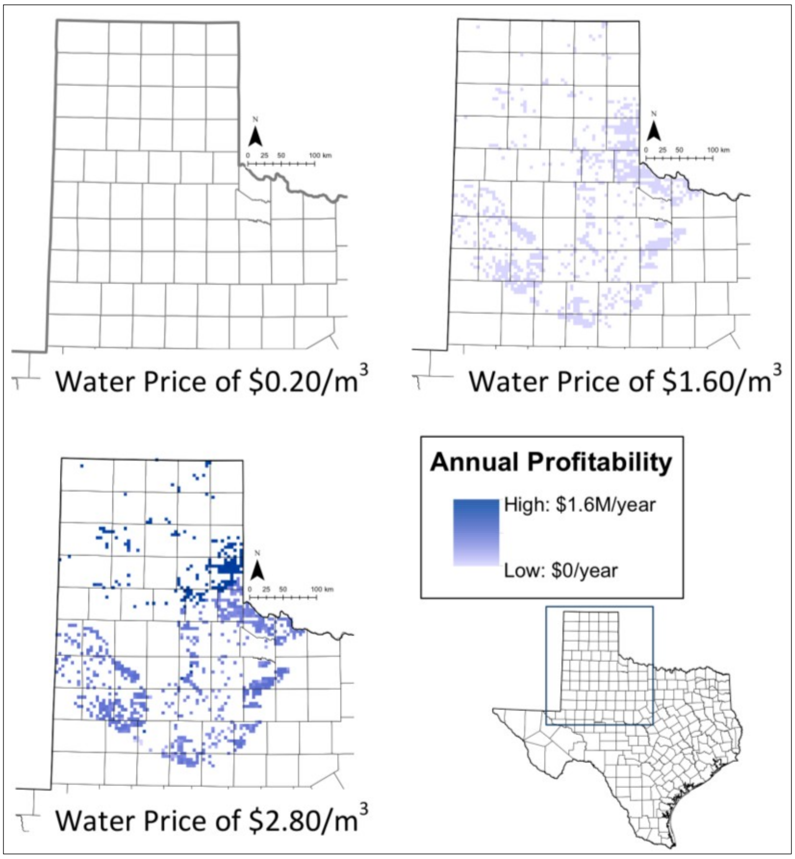
4.3. Geographic Analysis Results

ArcGIS was used to determine areas of overall feasibility of Scenario B, based on profitability and technical achievability. Profitability is normalized for an annual product water generation of 1,100,000 m^3/year, but presumably would scale up for larger systems. Areas of high annual profitability of an integrated wind-powered BWRO facility exist with up to $1,600,000 per year, based on the methodology presented considering a price of water of $2.80 per m^3 and average costs and the capacities as noted earlier and as shown in Figure 10. Areas of significant annual profitability are demonstrated for a moderate water price of $1.60 per m^3; however, no areas of profitability occur for a low water price of $0.20 per m^3. Annual profitability for representative wells are also tabulated with wind turbine capacity factors necessary to produce 1,100,000 m^3/year of product water based on the associated well depth, TDS, and wind classification, as shown in Table 5. Areas of greatest feasibility are concentrated in the Panhandle region of West Texas, including the major populations in the cities of Lubbock, Midland, and Abilene. Current and predicted future water demands demonstrate the need for additional water sources in these areas and suggest desalination of brackish groundwater as a water management strategy for both Midland and Lubbock counties [6]. Consequently, an integrated wind-powered BWRO facility might be a suitable solution to mitigating water shortages in Texas.

Table 5. Results for representative wells demonstrate the range in annual profitability based on brackish groundwater and wind conditions at the integrated facility.

	Brackish Groundwater and Wind Conditions	**Turbine Capacity (kW)**	**Water Price ($/$m^3$)**	**Profitability ($/year)**
	Depth: 50 m		$0.20	−$930,000
Well 1	TDS: 1000	505	$1.60	$570,000
	Wind Classification: 5		$2.80	$1,900,000
	Depth: 500 m		$0.20	−$1,200,000
Well 2	TDS: 10,000	1900	$1.60	$270,000
	Wind Classification: 5		$2.80	$1,600,000
	Depth: 500 m		$0.20	−$1,300,000
Well 3	TDS: 10,000	2660	$1.60	$130,000
	Wind Classification: 3		$2.80	$1,400,000
	Depth: 50 m		$0.20	−$970,000
Well 4	TDS: 1000	710	$1.60	$530,000
	Wind Classification: 3		$2.80	$1,800,000

Figure 10. Areas of profitable brackish groundwater desalination using wind-generated electricity are found in West Texas at a water price of \$1.60/m^3 and \$2.80/m^3. The cities of Lubbock, Midland, and Abilene are located within areas of profitability. At a water price of \$0.20/m^3, there are essentially no locations where the wind BWRO system is projected to be profitable.



5. Conclusions

This paper presented a method for estimating the energetic requirements and economic performance of an integrated wind-powered BWRO desalination facility. The method was demonstrated using industry-standard cost information, along with data on wind resources, brackish water resources, electricity prices, and water prices for the state of Texas. This work produced several conclusions.

First, although an integrated wind power and brackish groundwater reverse osmosis desalination facility requires a much larger capital investment, the profit provided from water sales might exceed the profit provided from intermittent, off-peak electricity sales of a stand-alone wind turbine. This outcome is primarily because the per-unit value of treated water is higher than the per-unit value of electricity.

Second, selling the wind generation directly to the power market is favorable when water prices are low and electricity prices are high. Using the wind generated electricity to produce treated water is favorable when electricity prices are low and water prices are moderate to high.

Third, areas of profitable brackish groundwater desalination using wind-generated electricity can be found in West Texas. The cities of Lubbock, Midland, and Abilene are located within areas of profitability.

Future work within the integrated renewable power and desalination facility area might consider integrated solar and wind to power the water collection and treatment processes. Integrating potable water storage into the analysis would provide interesting and practical insights into integrated renewables and desalination as a proxy for energy storage. Including transmission and distribution of water and electricity infrastructure considerations would further the application of this work. Also, optimal operation profiles could be generated to demonstrate maximum profitability scenarios based on temporal electricity pricing, wind resource output, and water demand.

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Conflicts of Interest

The authors declare no conflict of interest.

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