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**Methods for Evaluating the Potential to Power Industrial
Processes with Geospatially and Temporally Varying
Renewable Energy Resources**

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Sam Aminfard

DISSERTATION

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Dedicated to my parents Saeid and Fariba, and all of my family.

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Methods for Evaluating the Potential to Power Industrial Processes with Geospatially and Temporally Varying Renewable Energy Resources

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One pathway to decarbonizing global energy systems is to replace fossil fuels with renewable forms of energy such as solar and wind. However, the geo-spatially and temporally variant nature of these energy sources makes their integration into conventional electric grids a technically and economically onerous effort. By identifying processes compatible with intermittent renewable energy sources, energy-intensive industries can displace the need for fossil fuels globally while circumventing many of the barriers to integrating these energy sources into electricity grids. This dissertation assessed the techno-economic feasibility of utilizing wind and solar resources to meet the energy demands of desalination facilities, as well as electrified pneumatic control systems at oil and gas production sites.

The first study in this dissertation developed a method for assessing the technical and economic viability of using these renewable forms of energy to power brackish groundwater desalination facilities. The method relies on a multi-layered, spatial model that incorporated multiple variables such as depth of water resource, salinity levels, magnitude of local renewable energy resources, distance to water infrastructure, and, for comparative purposes, the local price of water. To illustrate this method, it was applied to 1,445 site locations on state of Texas lands owned by the General Land

Office that overlay brackish aquifer resources. Using this approach, 193 potentially economically viable sites were identified that have estimated renewable desalination water production costs lower than local municipal water prices. The results of this analysis showed that using wind to power a desalination facility is economically preferable to solar power at 145 of the 193 sites; solar was preferable at the remaining 48 sites. Solar and wind resources are both abundant in Texas; however, the particularly high capacity factors for wind across much of the state helps wind deliver electricity costs that are often lower than those provided by solar.

The second study sought to assess the technical and economic viability of using variable renewable energy to power electrified well site pneumatic control systems. Conventional pneumatic control systems vent methane-containing well gas during their operation. Electrifying these systems can avoid the venting of methane, which is a potent greenhouse gas. Under this study, two different strategies were considered for replacing pneumatic systems powered by well gas. One option is to exchange all components—controllers, actuators and pumps—to equipment that is directly powered by electricity. This scheme is referred to as the electric configuration. The second option, referred to as the electro-pneumatic configuration, is to retain the pneumatic system, but power its components with instrument air, which is ambient air that has been compressed by an electrically-driven compressor. This option thus replaces the emission of methane with ambient air. First, an energy simulator was developed to serve as a screening tool to determine the temporally-varying power demands incurred by switching a standard pneumatic system to an electrified one. The tool uses a comprehensive set of user inputs to simulate site-specific single-day power loads for the electric and electro-pneumatic configurations of well site control systems based on specifications from controllers, valve actuators, and chemical pumps commonly used at well sites. To assess the viability of meeting well site power loads with

intermittent renewable energy, electric and electro-pneumatic systems were modeled with solar photovoltaic (PV) power generation and electric battery storage during one year of typical conditions at sites located near Midland, Texas (Permian Basin), Nacogdoches, Texas (Haynesville Shale), and Edmonton, Canada (Kaybob-Duvernay Formation) using a time-resolved energy flow model. The electro-pneumatic model included a thermodynamic analysis to simulate storage of energy as compressed air in addition to electric battery storage. Of the two configurations, the all-electric option was found to be cheaper than the electro-pneumatic option while potentially supplying power to the system more reliably. An electric battery with a capacity of 1-2 kWh can deliver 100% reliability under typical meteorological conditions for the all-electric configuration utilizing a 200-250 W solar panel for sites located in Texas, resulting in a methane abatement cost of \$190-\$200 per ton of avoided methane emissions. The solar-powered electric system could potentially be employed at a well site in Alberta, Canada. However, because its solar resource is less abundant than in Texas, ensuring a high level of reliability would be 14% more costly. Other forms of on-site power generation such as geothermal energy might be more viable, or could possibly be used in conjunction with solar PV to ensure reliable operation during the winter when insolation levels are considerably lower. The higher power demands required by the electric air compressor in the electro-pneumatic design require larger PV generation capacity to achieve high levels of reliability. However, if the electro-pneumatic design is implemented, well-gas could potentially be used as a back-up to the air compressor to achieve equivalent reliability of the systems currently used in the field without the PV/battery system providing meet 100% of energy demands. While it is technically and economically feasible for electro-pneumatic systems to utilize compressed air tanks as the primary energy storage medium, electric batteries are the more viable option due to their energy density, stability and relative affordability.

For new well sites, the all-electric option will be more cost-effective. However, if electrification is performed as a retrofit, the electro-pneumatic configuration might be more cost effective if installing the electric system requires more than a week of downtime.

Together, these studies illustrate methods that can be used to assess the techno-economic viability of integrating variable forms of renewable energy into carbon and energy-intensive industries.

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Chapter 1

Introduction

1.1 Motivation

Transitioning from conventional use of fossil fuels without carbon capture to approaches that minimize the emission of greenhouse gases (GHG's) is essential to mitigating global climate change. Solar and wind energy can take a significant role in accomplishing this transition. However, adoption of these renewable energies has historically been hindered by capital and integration costs. The rapidly decreasing cost of wind turbines and photovoltaic systems in the past decade [2–4] has made wind and solar energy economically viable energy sources for electricity generation in many regions [5]. In 2017, wind and solar energy accounted for 28% and 22% of the electrical capacity added in the United States, respectively [6]. However, there are still several key hurdles to further integration of solar and wind into the global energy mix. The power produced by these technologies is intermittent, so they must be supplemented by baseload power (often with fossil fuels) [7], demand response [8], or energy storage to ensure total reliability [9]. In addition to temporal variation, geospatial variations preclude global adoption of solar and wind energy [5]. Many of these issues can be minimized by identifying specific processes that can be powered by intermittent energy directly to produce valuable resources. Potential resource production powered by renewables includes hydrogen production [10], brackish groundwater desalination [11–13], and fossil fuel extraction [14].

1.1.1 Powering Desalination with Renewable Energy

The availability of water with properties amenable to use by both industry and the general populace has become an issue of major significance in many places throughout the world. As populations continue to grow, the demand for water increases in commensurate fashion through the need for water intensive resources such as food and energy. The strain on readily-available fresh surface water can also be exacerbated by periods of drought, which creates urgency for municipalities and other entities to consider alternative sources of water. As a solution, fresh water can be transported across greater distances or acquired by treating low quality water [15]. However, these approaches are accompanied by increased energetic and economic costs. The production of energy often places a reciprocal strain on water resources since energy production is often a highly water intensive process [16]. Future demand for water should simultaneously, and intelligently, consider the demand for energy.

To meet increasing demands for water, alternative supplies that are abundant and relatively unaffected by changing climate are appealing. Brackish or saline water sources meet both of these criteria. However, water from these sources require desalting before use in municipal, agricultural, and most industrial applications. Despite its high energy intensity, desalination of seawater or inland brackish water is already employed in regions with significant constraints on the availability of fresh water [17]. However, this energy demand imposes technical and economic barriers to more widespread adoption. Desalination processes are generally powered by purchasing electricity from the grid. Work by Rao et al has shown that supplying all the potable water needs of water-stressed regions within 250 miles of United States coastlines would require approximately 0.5% of national electricity consumption [18]. Renewable energy sources such as wind and solar are appealing candidates for on-site

generation of electricity as they have no fuel costs and can help displace the need for fossil fuels. Furthermore, diverting power to desalination facilities can act as a proxy for energy storage or demand response, which opens up the possibility that the water treatment process could also provide grid reliability services. Combining renewable electricity generation and desalination facilities might enable broader adoption of these technologies.

1.1.2 Electrifying Oil and Natural Gas Production with Renewable Energy

Production of oil and natural gas has increased significantly in the United States since 2005 [19]. Increased domestic production has improved America’s energy economy by lowering natural gas prices and displacing coal-based power generation with cleaner gas-fired plants [6]. However, these energetic and economic benefits have been accompanied by a number of environmental concerns such as water use [20], flaring, liquid waste streams [21], and increased emissions of volatile organic compounds and nitrogen oxides (NO_x) [22] resulting from unconventional extraction methods such as hydraulic fracturing which have enabled the boom in fossil fuel extraction from shale resources. NO_x emissions are not vented directly from the well, but are emitted by combustion engines used during drilling, hydraulic fracturing, and gas compression. Interestingly, GHG emissions by the oil and gas industry have decreased slightly alongside increased oil and gas production [22]. This trend is due to voluntary and mandatory efforts to reduce emissions of greenhouse gases, particularly methane, at oil and natural gas production sites. Efforts have included identifying and repairing unintentional natural gas leaks, as well as replacing known sources of emissions such as pneumatic controllers and equipment driven by combustion of fossil fuels with cleaner electric alternatives. Despite these efforts, the oil and gas

industry is still a significant contributor to national GHG emissions. According to the Environmental Protection Agency (EPA), the petroleum and natural gas supply chain accounts for roughly 3% of total GHG emissions in the United States [23]. One third of supply-chain emissions stem from production operations while the remainder is emitted during transmission, processing, and storage.

Selection and utilization of available energy resources has a significant impact on the quantity of GHGs emitted by oil and gas production operations. Systems that control the operation of well sites must be supplied with a reliable source of power, which can be challenging at remote locations. One solution for delivering a reliable source of mechanical power is to utilize the pressure of the produced natural gas to drive pneumatic devices that control the operation of the well [24]. The design of pneumatic systems produces either a periodic or continuous vent of natural gas. The key drawback to pneumatic systems that utilize well gas is their emission of methane and volatile organic compounds as a result of the vent [22]. Methane, the main component of natural gas, is approximately 30 times more potent than carbon dioxide as a GHG over a 100-year period [25]. Though the emissions per system are relatively small on a volumetric basis [26], the cumulative impact of hundreds of thousands of pneumatic systems across the United States is significant. According to the EPA, natural gas-driven pneumatic pumps and controllers account for roughly 30% of all methane emitted by oil and gas production in the United States [23]. However, the bottom-up study by Alvarez *et al* has shown that the EPA might be underestimating production-phase methane emissions by up to 120% [27]. The majority of emissions from gas-controlled devices comes from a small number of devices — up to 95% of controller emissions result from 20% of pneumatic controllers [22]. Replacing these high emitting sources can decrease the amount of greenhouse gas and volatile organic compounds emitted by the oil and gas industry. To eliminate direct emission of these

gases, however, these units must be replaced with electric controllers or operated with compressed air [28].

Conventionally, electricity is sourced from fossil-fuel powered generators on-site or via transmission lines that connect to the local grid. Electrifying the field can reduce overall site emissions. However, sourcing electricity from the grid means that emissions are shifted to a different economic sector with varying environmental impacts depending on the fuel mix of each service areas power plants. Traditional on-site generators include compression ignition engines operated on natural gas or diesel, both of which emit GHGs [29]. Generating electricity at the well site with sources that have minimal emissions might help mitigate these challenges. When coupled with energy storage, renewable energy sources such as solar are appealing candidates for on-site generation of electricity as they can be deployed to remote well sites and produce no on-site emissions.

1.2 Scope and organization of dissertation

This work builds on previous geospatial analyses of powering processes with wind and solar energy as a pathway to decarbonize industries and improve utilization of renewable energy. This work develops methods that can be used to assess the techno-economic feasibility of utilizing wind and solar resources to meet the energy demands of desalination facilities, as well as electrified pneumatic control systems at oil and gas production sites. To address these concerns, this dissertation is structured through the following research objectives:

1. Implement a multi-layered geographic information system (GIS) model incorporating spatially-varying brackish groundwater desalination energy intensity and renewable energy availability for the state of Texas.

2. Develop a method to calculate the cost of desalinating brackish groundwater for any given location using data from GIS models as inputs.
3. Create a tool to calculate time-resolved power demands of electrified pneumatic control systems at oil and gas production operations.
4. Assess control equipment, renewable power generation, and energy storage options to reliably match electric loads and economically minimize methane emissions for natural gas well sites located in geographically-disperse North American shale regions.

The remainder of this dissertation is organized into four primary chapters. Chapter 2 discusses background information relevant to the analyses and case studies detailed in this dissertation.

Chapter 3 details a two-part analysis to assess the techno-economic viability of desalinating brackish groundwater in Texas. First, groundwater depth and salinity data were interpolated across the state of data from publicly-available well data to calculate the geo-spatial variation in the energy intensity of desalinating brackish groundwater. These calculations were combined with variables such as the magnitude of local renewable energy resources, distance to water infrastructure, and municipal water prices to develop a multi-layer GIS model (Objective 1). The second part of the analysis (Objective 2) developed a costing tool that used data from the GIS model as inputs to calculate the break-even cost of desalinating brackish groundwater with co-located wind or solar power generation at over 1,400 site locations on state of Texas lands owned by the General Land Office that overlay brackish aquifer resources. Calculated water production costs were then compared to local municipal water prices to down-select the most economically-viable site locations for the proposed desalination facility.

Chapter 4 discusses the methods developed to seek cost-effective pathways to minimize methane emissions at oil and gas well sites by electrifying pneumatic control systems with renewable energy. The first part of this analysis (Objective 3) developed a tool to estimate time-varying electric power loads of fully electric and electro-pneumatic well site control systems based on a customizable inventory of equipment and their scheduling parameters. Next, an energy-flow model was developed to determine how reliably time-varying well site power loads can be met with variable solar photovoltaic power generation over a full year of operation (Objective 4). Reliability and net present system costs were assessed as a function of location, electrification configuration, photovoltaic array size and energy storage capacity. The results of this analysis highlight solar-powered electrification options that minimize the cost of avoided methane emissions and maximize reliability for sites located in Texas and Alberta, Canada. Most of the work in Chapter 4 analyzes the integration of solar photovoltaic power generation at well sites. However, the potential to utilize distributed energy sources such as wind and geothermal at oil and gas wells is discussed here as well.

Finally, Chapter 5 summarizes the key conclusions of the analysis detailed in the previous chapters and outlines potential avenues for future research.

Chapter 2

Background

2.1 Powering Desalination with Renewable Energy

Texas is used as a testbed to illustrate the methods developed in Chapter 3 because it has growing water demand, abundant brackish water resources, and abundant renewable solar and wind energy. The 2017 Water Plan for the state of Texas outlined by the Texas Water Development Board (TWDB) projects the population of Texas to reach 29.5 million by the year 2020 [30]. This growth is expected to raise annual statewide water demand to 18.4 million acre-feet, a 34% increase from water use in 2014 [31]. In the event of a drought of record (referenced to the Texas drought of 1950-1957), there would be a water need of 4.8 million acre-feet based on projected demand in 2020. The second-worst drought in Texas history occurred as recently as the 2011-2014 period, with 2011 recorded as the worst single-year drought in history. These droughts and the projections for growth in water demand highlight Texas as a region that requires strategies for securing new, reliable water supplies.

Because of the abundance of brackish groundwater in Texas (Texas has 2.7 billion acre-feet of brackish groundwater [32]), desalination of water from brackish aquifers is a process with the potential to meet a significant portion of future water demands. Desalination is an appealing method as seawater and brackish groundwater are readily available during droughts. Brackish groundwater desalination (BGWD) is a proven technology in Texas as there are already 34 municipal plants with a combined capacity of 276,000 m³/day operating across the state as of 2015 [33]. Globally, there is

a cumulative desalination capacity of 74.7 million m^3/day [17]. Of this global capacity, 59.2% treats seawater and 20.9% uses (inland) brackish feedwater, while the remaining 19.9% of global capacity is used to treat wastewater or specialty applications, such as semiconductor manufacturing. In North America, 52.1% (5.0 million m^3/day) of installed desalination capacity processes brackish water. Brackish water and seawater are distinguished by their salinity. Source water salinity is measured as a function of total dissolved solids (TDS) in units of milligrams-per-liter (mg/L). The TDS of brackish groundwater generally falls between 1,000 to 10,000 mg/L, while seawater contains a TDS greater than 35,000 mg/L. Although inland brackish water can exist as surface water, the focus of this study is on brackish groundwater. The framework that is developed in Chapter 3 can be applied to desalination processes in general, however. Brackish groundwater is readily available not only in Texas but also across much of the United States, particularly California and Florida [34].

In addition to its significant brackish aquifers, Texas has abundant wind and solar energy. Texas is the largest generator of electricity by wind power, accounting for 57.6 of the 226 GWh of wind-based electricity produced in the United States in 2016 [6]. In addition to wind resources, the high levels of insolation and abundance of open land in Texas create a significant potential for PV generation. Figure 2.1 shows how the capacity factors for wind and solar power vary across Texas. Geographically-varying capacity factors for solar and wind were taken from literature [35] and historical data [36] respectively. Solar and wind resources are abundant in west Texas and the panhandle. It is this unique combination of resources, plus the demographic factors of economic and population growth, and Texas isolated grid that makes Texas a useful testbed for analysis. Narrowing the geographic scope further, this work in Chapter 3 focuses on estimating the cost of developing brackish water desalination facilities with collocated renewable power generation on parcels of land leased from

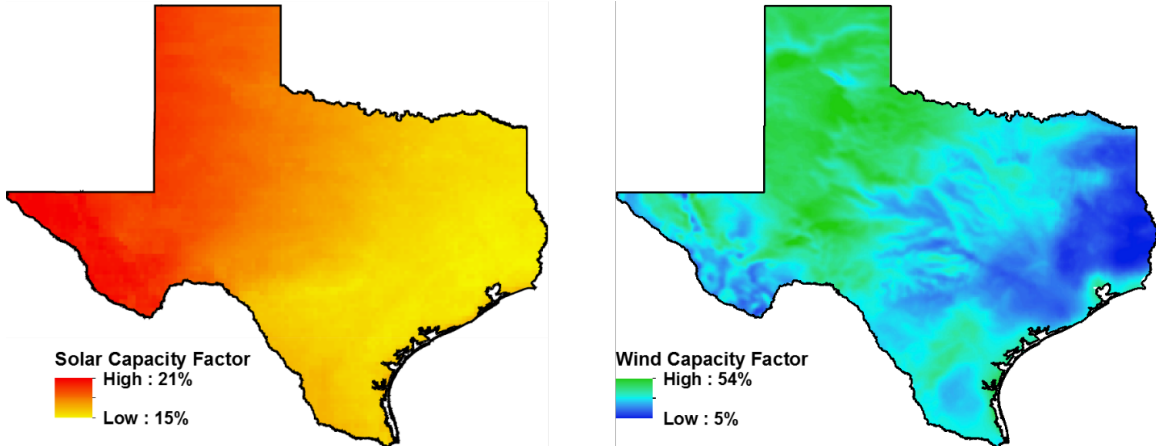


Figure 2.1: Geographically-varying capacity factors for solar photovoltaic (left) and wind turbine (right) power generation across Texas. Areas in west Texas and the panhandle have abundant solar and wind resources.

the Texas General Land Office (GLO). Many GLO parcels contain or are adjacent to oil and gas production operations, especially in the Permian Basin. These operations can serve as potential buyers of treated water [37]. The 1,445 GLO parcels examined in Chapter 3 have reasonable geographic distribution around Texas, and therefore serve as a useful proxy for the entire spatial span of the state. Furthermore, they are sufficiently numerous to yield key insights while also sufficiently limited to avoid severe computational burden.

There are several technologies that may be used for desalination processes, but reverse osmosis (RO) is by far the most common. RO accounts for 73.7% of the 50.0 million m^3/day global contracted capacity for the 2004-2014 period [17], and is also the process used by 44 of the 46 brackish water desalination plants operating in Texas [33]. The RO process operates by applying pressure to a solution to force the solvent across a selective membrane, thereby producing purified water while leaving behind a waste stream of highly-concentrated brine. Pumping requirements

and energy demand increase with increasing salinity of source water, and so desalination of seawater is considerably more energy intensive than brackish water [38]. The high cost of desalination processes stems from these significant energy requirements (13 kWh/m of treated water for brackish water and 34.5 kWh/m for typical seawater applications), in addition to considerable up-front costs for the treatment equipment [17]. The next-most common desalination techniques, multi-stage flash and multi-effect distillation, employ thermal processes that are more energy-intensive than RO. Solar energy can be coupled with multi-effect distillation through a solar pond or concentrated solar power (CSP), thus offering the potential to store energy as heat [39]. However, the land and direct solar insolation requirements of concepts such as CSP can preclude their viability in many regions. On the other hand, RO processes are generally driven by electricity, and are therefore compatible with renewable energy sources such as wind as well as solar. Furthermore, RO brackish groundwater desalination has been shown to be implemented economically at utility scale [33].

Coupling wind and solar photovoltaic panels (PV) has the potential to provide clean, low cost energy to desalination plants while also improving utilization of these intermittent energy sources. Though limited in scale, this paradigm has been applied to several desalination projects. A 15.9 million gallon per day (MGD) capacity seawater RO (SWRO) desalination plant powered by 15 MW of solar PV, and backed up by the national grid, is currently under construction in Al Khafji, Saudi Arabia [17]. In Sydney, Australia the Kurnell SWRO facility opened in 2010 is capable of producing up to 66 million gallons of treated water per day and is partially powered by a 140 MW wind farm. While these are the largest examples of combined renewable energy and desalination facilities, there have been many other smaller-scale projects located around the world. In the city of Seminole, Texas, researchers from Texas Tech University successfully operated a pilot-scale brackish groundwater RO plant powered by

a 50 kilowatt (kW) wind turbine for one year [40].

Desalination projects with integrated solar PV and wind power generation have shown the feasibility of the concept. These facilities generally must be supported by power from the local grid to ensure continuous operation of the RO processes. However, the potential exists to vary the production of treated water without damaging RO membranes as the availability of renewable energy fluctuates temporally [41, 42]. Several studies have shown how PV systems coupled with RO units can be optimized to maximize the variable output of desalinated water without the need for energy storage or connection to a power grid in regions of high solar availability [43–45]. Varying the power demand of the RO facility by stepping down treatment output can also enable sales of excess power when electricity prices are high. Coupling renewable energy with desalination has the potential to improve the economic feasibility of the combined facility while also serving as a proxy for grid-level energy storage or demand response.

The technical and economic viability of desalination powered by renewable energy has been examined in a number of studies. The cost and energy demand of small-scale desalination units powered by solar, wind, and geothermal energy have been shown to vary considerably based on the type of energy or desalination technology employed [39]. Research has shown the potential for solar photovoltaic (PV) with reverse osmosis (RO) as a viable method for desalination of both seawater [40] and brackish groundwater [11, 44]. Related studies have analyzed the viability and economics of desalinating brackish groundwater by coupling wind turbines with RO facilities [12, 13]. These studies examine the feasibility of PV or wind-powered desalination separately, and, to some extent, account for geographic variability of this feasibility. However, there are currently no publicly available methods for estimating

the comprehensive cost of a solar or wind-powered brackish groundwater desalination facility that account for geospatial variations in RO desalination energy intensity, renewable energy availability, and distance to water infrastructure. The focus of the research discussed in Chapter 3 is to establish the framework for such a tool. Furthermore, this work employs data on local water prices to determine the economic viability of solar and wind-powered brackish groundwater desalination compared to existing fresh water markets within a given region.

2.2 Electrifying Oil and Natural Gas Production with Renewable Energy

Three North American oil and natural gas-producing shale regions were selected to illustrate the methods developed in Chapter 4: the Permian Basin, the Haynesville Formation and the Kaybob-Duvernay Formation. These geographically disparate regions were selected for their variation in renewable energy resources, particularly solar energy. The locations of these regions and the relative variation in solar availability is shown in Figure 2.2. The increasing levels of operational activity in these regions also makes them appealing test beds to target GHG mitigation techniques. Natural gas production in the Permian has increased from approximately five billion cubic feet per day in 2011 to nearly eleven billion cubic feet per day in 2018 [46]. As of August 2018, operations in the Permian and Haynesville regions account for 30% of natural gas produced in the United States and production levels continue to increase. The Kaybob-Duvernay shale formation located in Alberta, Canada is an emerging oil and natural gas-producing region that is estimated to hold 443 Tcf of natural gas [47]. Production levels in this regions are still relatively low. However, Chevron has already begun a pilot program to implement distributed electricity generation with solar PV, fuel cells and a microturbine powered by well gas [48]. While

electrification has already begun to reduce the emissions accompanying development of wells in the Permian Basin, the power demand in the area is projected to climb to 1 GW by 2022, compared to 22 megawatts in 2010 [49]. Alternative energy sources, such as on-site solar, have the potential to reduce the environmental footprint of the region.

The power demands at oil and gas production sites are highly variable, but present opportunities for integration of alternative energy sources. The highest demand for fossil energy consumed at production-phase oil and gas sites derives from heating processes and drivers (motors) for large compressors and down-hole pumps. The energy demands and GHG emissions of these processes have been well-documented by the Oil Production Greenhouse Gas Emissions Estimator (OPGEE) developed by El-Houjeiri et al [9]. OPGEE can estimate the power loads and GHG emissions of the most energy-intensive equipment utilized during each step of a well’s life cycle. However, it cannot be used to track acute variations in power load or methane emissions encountered during a typical operational day during the production. Work by David Allen *et al* has quantified temporal fluctuations in GHGs and other air pollutants emitted by production-phase well sites extensively [50, 51]. Compared to heaters and drivers, pneumatic devices have low energy and power demands but still account for roughly 30% of all methane emitted by oil and gas production in the United States due to the operational procedure of venting well gas [23]. This study detailed in Chapter 4 focuses on pneumatic devices due to their relatively large contribution to GHG emissions; however, future work could consider how to incorporate renewable energy sources to power other on-site equipment, such as heaters.

Pneumatic control systems at unconventional natural gas wells commonly include three major components: controllers, actuators, and pneumatic pumps. In this

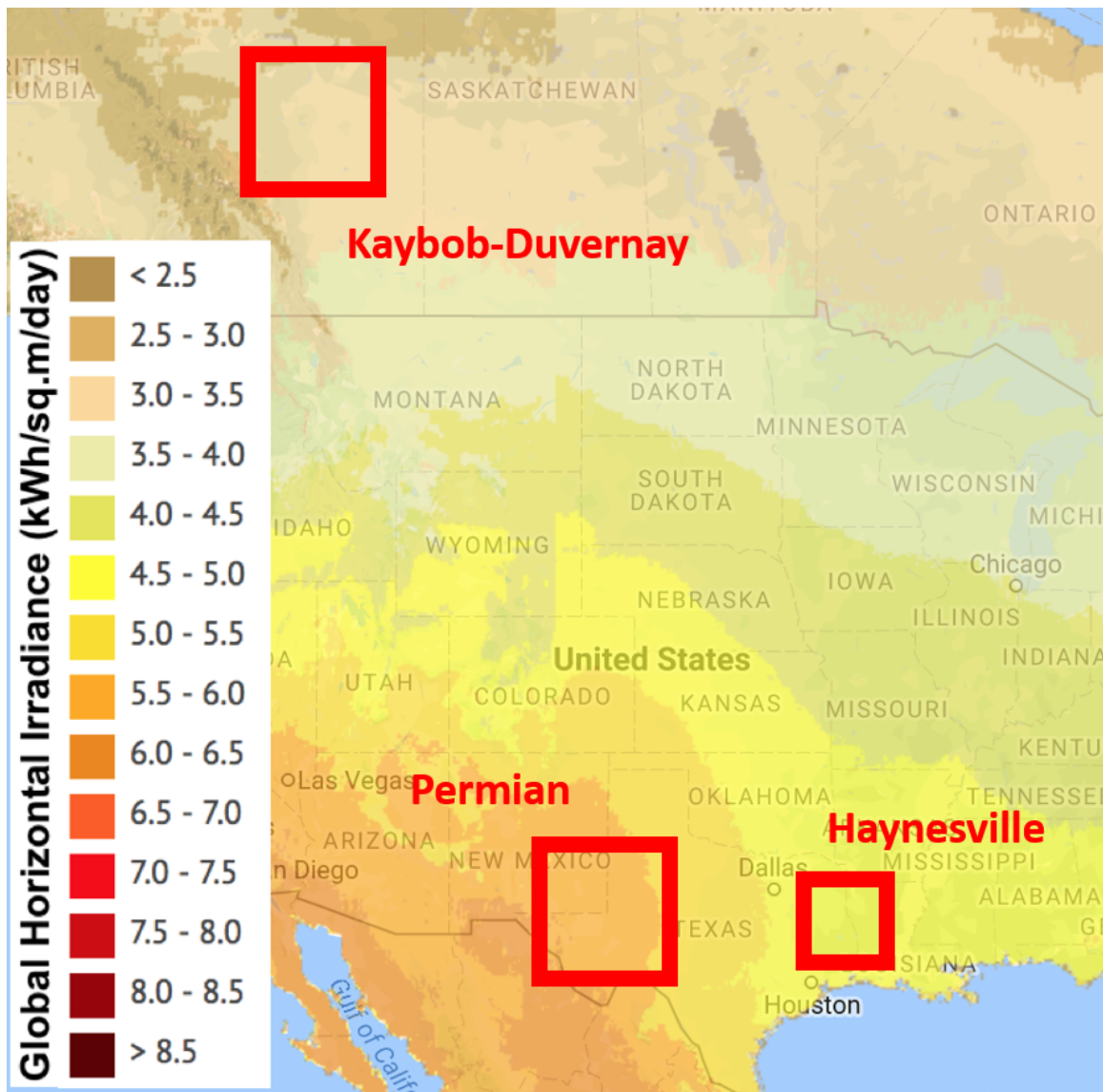


Figure 2.2: Variation in solar availability across North America [1]. The red boxes indicate the locations of the Haynesville Formation, Permian Basin, and Kaybob-Duvernay Formation located in eastern Texas, western Texas, and western Canada respectively

case, a controller combines sensing and decision-making, the latter of which can be done by set points, computers, programmable logic devices, and so forth. For example, a controller might include a sensor that detects a process parameter such as pressure, liquid level (as in Figure 2.3), or temperature, after which it will transmit a signal to an actuator once the detected parameter falls outside the bounds of a set value [24,28]. In a pneumatic system, this signal is transmitted via supplied well gas typically adjusted to a pressure of 20 to 50 psi. A significant portion of emissions occur at the controller since they are often designed to intentionally bleed a portion of the supply gas, either continuously or intermittently. The pneumatic signal is typically transmitted to a diaphragm valve actuator, which will then actuate or stop actuating depending on the system configuration. Pneumatic pumps utilize pressurized well gas to power an integrated motor. The motor draws fluid from a reservoir into the pump and discharges it at the pressure required by the process. These pumps typically are used to deliver chemicals such as hydrate inhibitors and surfactants. A schematic of a typical well site pneumatic control system is shown in Figure 2.3.

Saunier *et al* have evaluated the cost-effectiveness of reducing well site methane emissions by electrifying pneumatic control systems under a number of scenarios [52]. They determined that replacing pneumatic controllers with fully-electric equivalents can result in methane abatement costs below the 2016 U.S. Environmental Protection Agency (EPA) social cost of methane (\$1,354 per ton of methane) for sites with up to twenty controllers that are connected to the electric grid. Methane abatement costs were evaluated relative to the cost and methane emissions of a standard pneumatic control system operating on well gas. Electricity supplied by the local electric grid is the lowest-cost and most common option to power electrified well site systems. However, many well sites are located in remote areas where building a connection to a power grid is technically or economically infeasible. While electrifying pneumatic

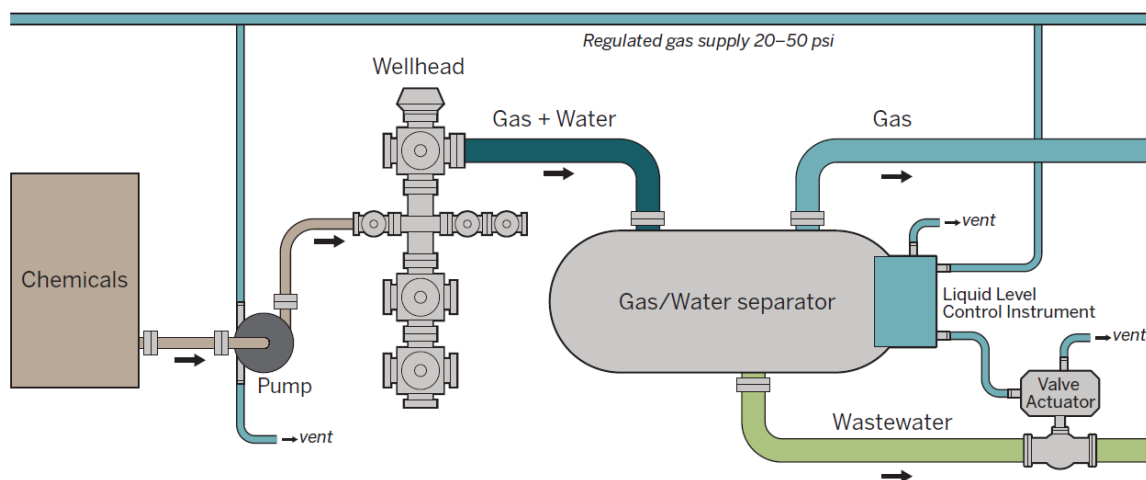


Figure 2.3: Schematic of pneumatic equipment typically found at an oil and gas well site.

systems with grid power will significantly reduce methane emissions, power supplied by most electric grids will have associated GHG emissions produced by fossil fuel power plants. For sites without a grid connection, powering electric controllers with solar PV was found to be ten to one hundred percent more costly, but the methane abatement costs of these systems were generally still below the social cost of methane. Compressed air systems were found to be more economical at sites with more than 20 controllers and a reliable connection to an electric grid, but the report did not examine the cost of powering compressed air systems with solar PV. Furthermore, they used engineering assumptions that did not account for temporal and geo-spatial variations in solar energy availability and power loads.

Powering well site processes with renewable forms of energy such as solar, wind, or geothermal energy has the potential to reduce GHG emissions of oil and gas production. Investigations of utilizing wind turbines at oil productions sites have been limited to illustrating how wind power can be used to supplement power from

the electrical grid [53, 54]. One promising application currently being tested is to utilize wind power to pump water into offshore oil wells [55]. The concept of a solar-powered well site with an air compressor has existed for decades [49], but such a paradigm has only become technically and economically feasible in recent years as a result of improvements in PV cell efficiency and rapidly declining PV system costs [2–4]. Solar PV presents the most modular power generation option as compared to wind or geothermal energy which rely on turbine-based power generation. The generation capacity of solar PV systems can be easily scaled up or down at increments of 25-50 W by the number of panels integrated in the system. Furthermore, the cost of solar PV presents an affordable option for producing electricity renewably at small scale. Solar PV systems backed up by electric batteries can potentially power well sites more economically than on-site conventional fossil fuel generators such as diesel generators or natural gas microturbines, which are less modular and can generally only be scaled at the kilowatt level. These fossil fuel-powered generators also incur higher operational and maintenance costs than PV systems. Unlike diesel generators or natural gas microturbines, solar PV systems have no fuel costs and produce no on-site GHG emissions. Solar PV systems backed up by electric batteries can potentially power well sites more economically than on-site conventional fossil fuel generators such as diesel generators or natural gas microturbines, which are less modular and can generally only be scaled at the kilowatt level. These fossil fuel-powered generators also incur higher operational and maintenance costs than PV systems. Unlike diesel generators or natural gas microturbines, solar PV systems have no fuel costs and produce no on-site GHG emissions. Research has shown that solar energy can supply up to 0.08 exajoules (EJ) of electricity (photovoltaic) and 0.38 EJ of thermal energy (solar thermal) per year to world-wide upstream oil and gas processes [49]. Solar thermal energy can be a promising method of utilizing

solar resources for process heat, particularly steam generation utilized by enhanced oil recovery [56]. While 0.46 EJ is equivalent to only 4-5% of the global energy demand for upstream processes, utilization of solar energy might be more concentrated in certain regions due to geo-spatial variations in solar resources and the energy intensity of processes. Solar photovoltaic (PV) power is a proven technology at oil and gas wells. For example, manufacturers of well site components such as chemical pumps already offer electric options integrated with PV panels and batteries [28, 57]. In addition to its low cost, PV technology is modular and easily transportable, which facilitates integration of PV power generation into remote well fields. The adoption of solar PV will require additional logistical considerations, such as space requirements within active well pads, as well as mitigating the potential for PV panels becoming the target of theft or vandalism.

The viability of utilizing renewable energy to power oil and gas production processes has been examined by a number of studies. Research has shown the potential for solar energy to supply both electricity (photovoltaic) energy for upstream oil and gas processes at a global or regional scale [49, 52, 56]. Currently, no studies have accounted for the temporal variations in well site power loads and energy availability, which are the key barriers to utilization of solar and wind power in oil and gas production on a site-by-site basis. The study detailed in Chapter 4 characterizes transient well site power loads and solar energy availability and identified economically feasible configurations of power generation and energy storage to ensure reliable operation of processes. Furthermore, this study examines coupling solar photovoltaic generation with both fully electric equipment and electrically-powered compressed air well site systems as pathways to reduce the emissions of oil and gas production. A qualitative examination of wind and geothermal power generation at well sites are also discussed in Chapter 4 as potential alternative energy sources for well fields with

low solar availability and high power demands.

Chapter 3

Assessing Geo-Spatial Variations in the Techno-Economic Viability of Using Renewable Energy to Power Brackish Groundwater Desalination

3.1 Methods

3.1.1 Geospatial Variability of Desalination Energy Intensity

The energy required to desalinate a given volume of brackish groundwater depends on the energy needed to pump the water up to the surface and the energy demand of the RO process [11]. This dependency is expressed as

$$EI_T = EI_{RO} + EI_P \quad (3.1)$$

where EI_T , EI_{RO} , and EI_P are the total energy intensity of desalination, the energy intensity of pumping water to the surface, and the energy intensity of the RO process, respectively. Energy intensity is quantified in joules per cubic meters of treated water (J/m^3). Table 3.1 provides additional detail regarding the variables used herein .¹

¹The work discussed in this chapter has been published previously (S. Aminfard, F.T. Davidson, and M.E. Webber. Multi-layered Spatial Methodology for Assessing the Technical and Economic Viability of Using Renewable Energy to Power Brackish Groundwater Desalination, *Desalination*, vol 450, pp. 12-20, January 2019.) The author of this dissertation developed and carried out all analysis and modeling in this work, and wrote the manuscript.

Table 3.1: Summary of abbreviations and key costing analysis parameters and variables. The values of parameters consistent throughout the analysis are shown in the third column, otherwise only units are indicated.

Symbol	Definition	Value [Units]
c_{BE}	Break even cost of treating water	[\$/kgal]
c_{DS}	Debt service i.e. amortized total capital costs	[\$/year]
C_I	Interest accrued during construction	[\$]
C_L	Total construction financing required before interest	[\$]
C_{Pi}	Piping cost	[\$]
C_{PS}	Pumping station cost	[\$]
C_{RO}	Desalination plant cost	[\$]
C_T	Total capital cost	[\$]
C_{well}	Well cost	[\$]
$C_{W/PV}$	Installation cost of either wind or solar facilities	[\$]
$CF_{W/PV}$	Capacity factor for wind or solar photovoltaic panels (PV)	[%]
D	Well depth	[m]
EI_P	Energy intensity of pumping water to the surface	[J/m ³]
EI_{RO}	Energy intensity of the RO process	[J/m ³]
EI_T	Total energy intensity of desalination	[J/m ³]
P_P	Power needed for pumping from well	[W]
P_{RO}	Power needed for desalination	[W]
P_T	Total power needed	[W]
$P_{W/PV}$	Generation capacity of either wind or solar photovoltaic panels (PV)	[W]
r_{EC}	Engineering and contingencies rate	35%
Q_{cap}	RO plant capacity	[m ³ /s]
Q_{well}	Total flowrate of water withdrawn from the well	[m ³ /s]
TDS_{well}	Groundwater salinity	[mg/L]
η	Pump efficiency	65%
γ	Specific weight of water	9.81103 [N-m ³]
Abbreviation	Definition	
BGWD	Brackish Groundwater Desalination	
GIS	Geographic Information System	
GLO	General Land Office	
kgal	Thousand gallons	
MGD	Million gallons per day	
NREL	National Renewable Energy Laboratory	
PV	Photovoltaic	
RO	Reverse Osmosis	
SWI	Saltwater Injection	
SWRO	Seawater Reverse Osmosis	
TCEQ	Texas Commission on Environmental Quality	
TDS	Total Dissolved Solids	
TWDB	Texas Water Development Board	
UCM	Unified Costing Model	

The energy intensity of RO is assumed to be a linear function of the salinity

measured as total dissolved solids (TDS) present in the brackish groundwater denoted below as TDS_{well} . The following function was derived from previous work by Stillwell and Webber [38]

$$EI_{RO} = 316.8 \times TDS_{well} + 13680000 \quad (3.2)$$

The relation provided in Equation 3.2 was originally derived from empirical RO plant data and includes the energy requirements of water pre-treatment. Energy demands might deviate from this relation as conditions will vary between proposed facilities and the plants examined by Stillwell and Webber [38]. To calculate the energy demands of RO processes more accurately, detailed analyses considering specific process equipment and conditions must be applied on a site-by-site basis [45]. However, the methodology outlined here assumes Equation 3.2 provides a first-order energy load estimate that is broadly applicable for the comparative analysis of this work. The energy intensity of pumping water to the surface, EI_P , is defined as

$$EI_P = \frac{\gamma \times D}{\eta} \quad (3.3)$$

where:

γ : specific weight of water [$9.81 \times 10^3 \text{ N-m}^3$]

η : pump efficiency [65%]

D: well depth [m]

Calculations for the energy intensity of pumping, EI_P , assume the RO plant is within close proximity to the well and do not account for transport of water beyond the facility. Furthermore, it is assumed that the depth of the water is equivalent to the reported depth of the well. In reality, the groundwater level might be above

the reported depth of the well, offsetting some of the hydraulic head requirement to bring the water to the surface. As such, the calculations for energy intensity of pumping may be considered a worst-case scenario. The final expression for EI_P and its constants were taken from literature [11].

Equations 3.1 to 3.3 infer that the key, site-specific variables that determine EI_T are brackish groundwater salinity TDS_{well} and well depth D . Because data on water characteristics are only available with coarse spatial resolution, information collected by the Texas Water Development Board (TWDB) [58] for individual wells was spatially-interpolated across the entire state to estimate groundwater characteristics for any given location in Texas. All interpolation was carried out in ArcGIS using the Spherical Kriging Interpolation tool. Before interpolating well data, wells shallower than 10 feet were removed from the dataset as these wells are likely used for monitoring purposes and might not accurately reflect local aquifer characteristics [59].

Initially, TDS values were interpolated across the entire state for all wells deeper than 10 ft, as in Figure 3.1 (A). Areas where the interpolated TDS is less than 1,000 mg/L were identified and removed as water with that salinity is considered freshwater and this work is focused on regions with only brackish groundwater, as shown in Figure 3.1 (B) and (C). The interpolated well depth and TDS data were used to estimate the energy intensity of desalinating brackish groundwater, measured in kilowatt-hours per thousand gallons of purified water (kWh/kgal) as shown in Figure 3.1 (D). The results show that the energy intensity varies by up to an order of magnitude across the entire state.

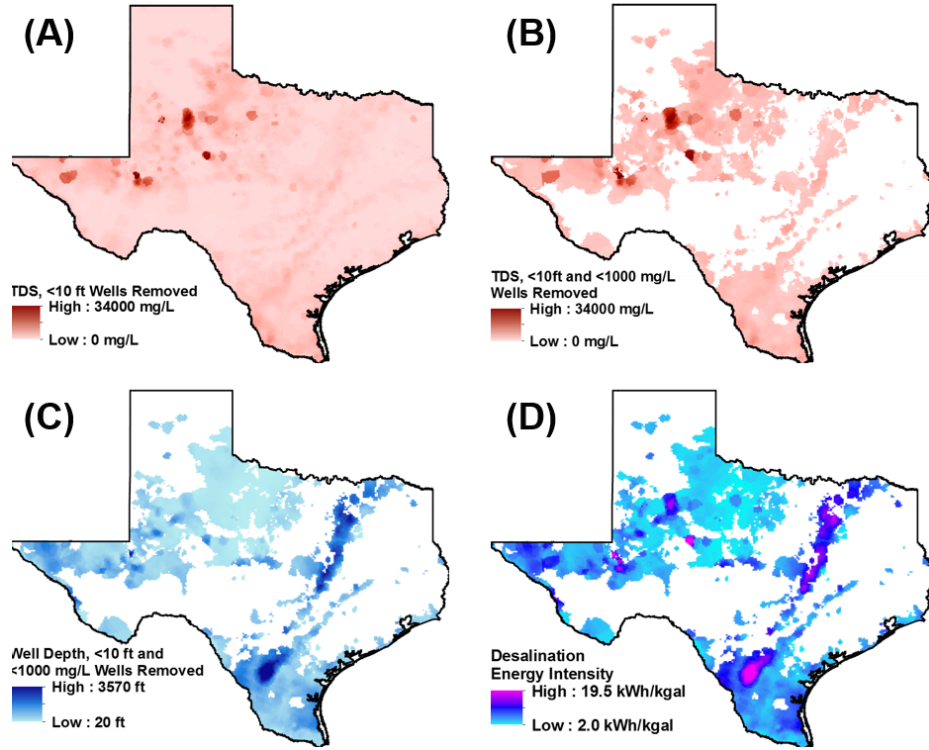


Figure 3.1: Data for brackish groundwater salinity (in TDS) (A and B), well depth (C), and the resulting energy intensity of desalination (D) interpolated across Texas. The maps shown in (B) and (C) are modified to remove zones where brackish groundwater is likely not present (areas in white).

3.1.2 Geospatial Variability in Water Infrastructure and Pricing

The economic viability of a potential renewables-powered BGWD project can be gauged by comparing calculated water costs with local water prices. Water rates were collected from the Texas Municipal League for 640 municipalities in Texas [60] and projected across the state as shown in Figure 3.2. Water pricing structures vary considerably for different municipalities, so local water rates were approximated from the available figures reported as residential (10,000 gallon) and commercial (200,000 gallon) fees.

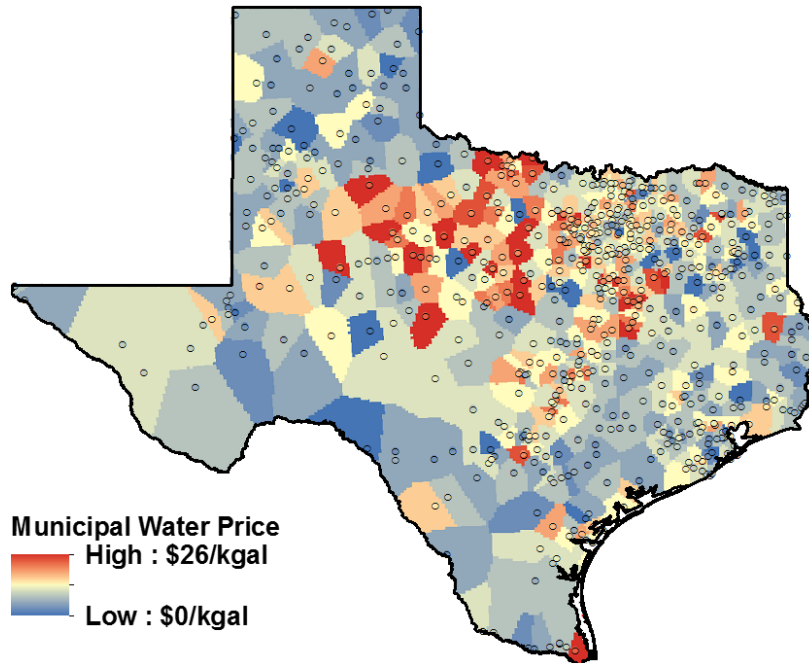


Figure 3.2: Regionally-varying municipal water prices across Texas. Dots indicate the location of each municipality. Zones were created by mapping every location in Texas to the nearest municipality and assigning the local municipal water price to each respective

The distance to existing water infrastructure from any given point within Texas was incorporated in the GIS model to estimate the amount of piping required to transmit purified water from a potential desalination plant to users. Data on the location of existing water infrastructure was unavailable for all of Texas, so GIS data for public water system wells and surface water intakes acquired from the Texas Commission on Environmental Quality (TCEQ) was used as an approximation [61]. The distance to existing public water wells and surface intakes was then calculated for any point within Texas. This value was used to approximate the length of pipeline needed for a potential desalination project at a given location. Pipeline costs are included to account for the potential cost of transportation as RO is best utilized as

a large-scale desalination process. As shown in Figure 3.3, the most remote areas will require almost 65 kilometers (40 miles) of piping to transmit treated water to potential users.

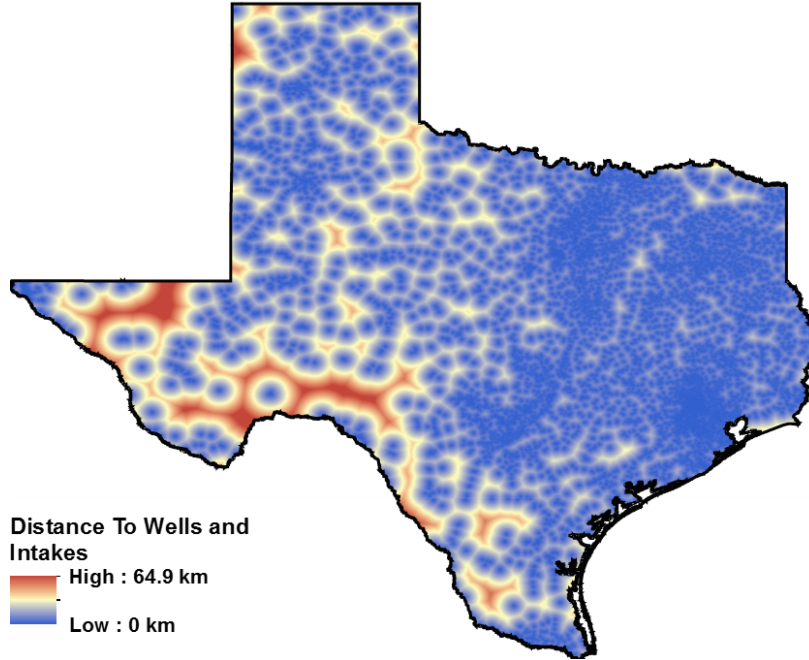


Figure 3.3: The distance to public water system wells and intakes calculated for any given point in Texas

3.1.3 Integrated Facility Costing Model

The model developed in this work for estimating the cost of constructing and maintaining a wind or solar-powered brackish groundwater desalination facility is based on the TWDB Unified Costing Model (UCM) used in the Texas state and regional water plans [62]. The UCM includes capital costs, maintenance costs, and financing parameters for construction of RO plants, brackish groundwater wells, pumping stations, and transmission piping. These costing estimates are based on

governmental and industry standards that are applicable to development of water treatment projects within the state of Texas. Costs might vary on a site-by-site basis, but the UCM provides reasonably accurate costing standards for the large set of proposed facilities examined here. For this study, the UCM was modified to use GIS data as inputs for calculating costs, and to incorporate the cost of building renewable energy capacity (wind turbines or photovoltaic arrays) and brine disposal facilities. Power demands and the required renewable energy capacity for the integrated facility were calculated with the following expressions.

$$P_{RO} = EI_{RO} \times Q_{cap} \times [0.04381 \frac{m^3/s}{MGD}] \quad (3.4)$$

$$P_P = EI_P \times Q_{well} \times [0.04381 \frac{m^3/s}{MGD}] \quad (3.5)$$

$$P_T = P_{RO} + P_P \quad (3.6)$$

$$P_{W/PV} = \frac{P_T}{CF_{W/PV}} \quad (3.7)$$

where

P_{RO} : Power needed for desalination [W]

P_P : Power needed for pumping from well [W]

P_T : Total power needed [W]

$P_{W/PV}$: Capacity to install either wind or solar (PV) [W]

$CF_{W/PV}$: Capacity factor of wind or solar [%]

The RO facility is assumed to have a recovery factor of 80% and produce treated water with a salinity of 500 mg/L [62]. Therefore, a greater volume of water must be withdrawn from the brackish well than the desired volume of treated water, i.e. Q_{well} will be greater than Q_{cap} . Calculations of Q_{well} and a diagram of RO plant flows are shown below and in Figure 3.4.

$$Q_{blend} = Q_{cap} \times \frac{TDS_t}{TDS_{well}} \quad (3.8)$$

$$Q_{RO} = \frac{Q_{cap} - Q_{blend}}{R} \quad (3.9)$$

$$Q_{well} = Q_{blend} + Q_{RO} \quad (3.10)$$

where:

Q_{blend} : Flowrate of water withdrawn for blending to achieve TDS_t [MGD]

Q_{RO} : Flowrate of water withdrawn for desalination [MGD]

Q_{well} : Total flowrate of water withdrawn from well [MGD]

R : Desalination recovery factor [80%]

TDS_t : Total Dissolved Solids of treated water [500 mg/L]

The term Q_{brine} represents the flow rate of concentrated brine produced as a byproduct of the desalination process. Brine must be disposed of and will incur additional costs which will vary depending on the disposal method. To account for the cost of disposal, this analysis assumed that a salt water disposal (SWD) well must be drilled for each potential project at a cost of \$3 million.

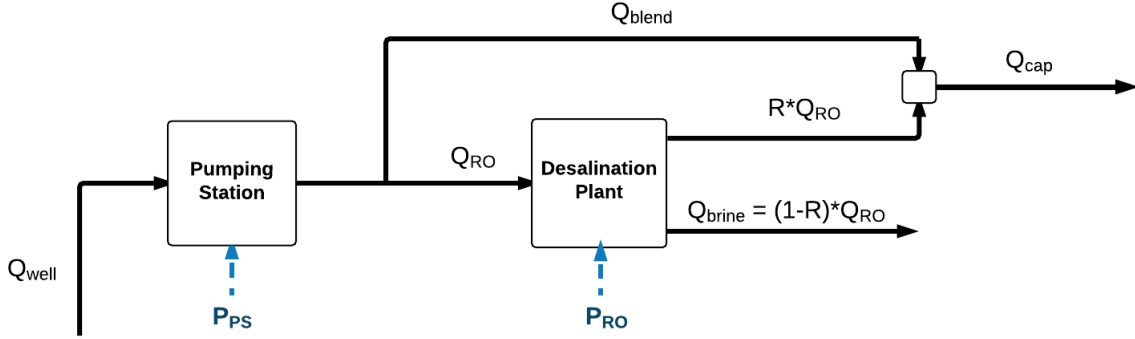


Figure 3.4: Diagram describing flows of water and power into and out of the desalination facility. Water flows into the plant from the brackish groundwater well and exits as streams of treated water and waste brine.

Calculations of the required wind or PV capacity are made such that, over the course of the year, enough energy will be generated to meet all RO and pumping demands. Daily fluctuations in renewable power generation were assumed to be balanced by the electrical grid, allowing for the purchase of electricity when renewable generation is low and the sale of electricity when excess renewable generation is achieved. Electricity purchases were assumed to be equal to total electricity sales for the entire year, thus resulting in a net zero cost of purchased electricity, though actual wholesale market transactions or bilateral contracts could generate different results depending on the operational scheme and year. For example, excess solar power will often be generated during the middle of the day when electricity can be sold on the wholesale market at higher rates, thereby balancing or even exceeding electricity purchases at other times [12]. However, facilities utilizing wind in West Texas might incur higher electricity costs as generation will be at its lowest in the middle of the day and electricity must be purchased at higher rates to ensure operation of the RO facility. Electricity purchases for wind-powered plants will be limited, particularly at

night and in the early morning, thanks to the higher capacity factors available to wind than solar. Assuming a net zero cost of purchased electricity might underestimate operational costs under some scenarios. However, this methodology allows for computationally efficient first-order assessment of the geo-spatial variations in PV and wind capacity requirements at a large number of sites. In order to assess the cost of electricity most accurately, electricity purchases and sales must be assessed on a site-by-site basis. Future work should incorporate more detailed temporal assessment of on-site generation and demand, including stochastic modeling, as well as local daily and seasonal grid electricity prices, but such detailed analysis is beyond the scope of the work presented here.

The geographically-resolved capacity factors for wind and PV ($CF_{W/PV}$) are taken from the GIS model and can be seen in Figure 2.1. Total installation and maintenance costs for renewable energy capacity are calculated based on the required power capacity $P_{W/PV}$ and unit (\$/W) costs acquired from the National Renewable Energy Laboratory (NREL) [3]. Distance to the nearest water infrastructure for each site was taken from the GIS model to estimate the necessary length and total cost of transmission pipeline. Water production costs were calculated in terms of dollars per thousand gallons (\$/kgal) by normalizing annual financing and maintenance costs with the total yearly water production. Financing costs c_{DS} were calculated based on the total capital cost c_T for the integrated facility described in Equations 3.17-3.19. Financing calculations assumed a twenty-year debt service period and 5.5% interest rate. Default maintenance costs from the UCM were applied to the pump, well, and pipeline; however, costs for desalination plant maintenance were taken from literature to avoid including the cost of power [13]. The final expression for the break-even cost of producing water c_{BE} is shown in Equation 3.27. The lower case variables in this equation indicate a yearly maintenance cost, instead of a capital cost. The calculation

of all capital costs, interest, annual debt service, and operational expenditures are detailed below.

3.1.3.1 Capital Cost Equations

The equations below detail all capital costs accounted for a solar or wind-powered brackish groundwater desalination facility at each location. Inputs from the GIS model were used to size water processing equipment and renewable electricity generation capacity. Next, capital costs for these facilities were interpolated from data tables based on the necessary equipment capacities. Costing and flow rate calculations are taken from the UCM developed by the TWDB [62]. This tool provides costing estimates based on governmental and industry standards that are applicable to development of water treatment projects within the state of Texas. Variables denoted by an asterisk are inputs to the costing model from geographically-resolved data. Data for many variables were available for all sites across Texas. However, brackish well water salinity and well depth were geospatially interpolated from sparse point data. The term $f(x)$ used to describe cost variables indicates that the cost was interpolated from a data table based on the variable x .

C_{EC} : Engineering and contingencies [\$]

C_I : Interest accrued during construction [\$]

C_L : Total construction financing required before interest [\$]

C_{Pi} : Total piping cost [\$]

C_{PS} : Pumping station cost, $f(P_{PS})$ [\$]

C_{RO} : Desalination plant cost, $f(Q_{cap}, TDS_{well})$ [\$]

C_S : Construction subtotal [\$]

C_T : Total capital cost [\$]

C_{well} : Well cost, $f(D, Q_T)$ [\$]

$C_{W/PV}$: Installation cost of wind or solar capacity[\$]

d_{Pi} : Pipe diameter [in]

L : Distance to closest public wells or intakes (piping length) [ft]*

P_{PS} : Pumping station capacity [hp]

r_{EC} : Engineering and contingencies rate [35%]

r_I : Interest rate [5.5%]

r_R : Return on investment [1.0%]

t_C : Project construction period [2 years]

u_{Pi} : Unit pipe cost, $f(d_{pi})$ [\$ /ft]; assumed constant

$u_{W/PV}$: Unit capacity cost of wind or solar, $f(P_{W/PV})$ [\$ /W]

v : Water velocity in pipe [2.134 m/s]

$$P_{PS} = \frac{\rho \times g \times (D - H_p)}{\eta} \times [0.001341 \frac{hp}{W}] \times Q_{well} \times [0.04381 \frac{m^3/s}{MGD}] \quad (3.11)$$

If $D < H_p$, $P_{PS} = 0$

$$d_{Pi} = \sqrt{\frac{4Q_{cap} \times [0.04381 \frac{m^3/s}{MGD}]}{v\pi}} \times [39.3701 \frac{in}{m}] \quad (3.12)$$

$$C_{Pi} = u_{Pi} \times L \quad (3.13)$$

$$C_{W/PV} = u_{W/PV} \times P_{W/PV} \quad (3.14)$$

$$C_S = C_{RO} + C_{Pi} + C_{well} + C_{PS} + C_{W/PV} \quad (3.15)$$

$$C_{EC} = r_{EC} \times C_S \quad (3.16)$$

$$C_L = C_S + C_{EC} \quad (3.17)$$

$$C_I = r_I \times C_L \times t_C - \frac{C_L}{2} \times r_R \times t_C \quad (3.18)$$

$$C_T = C_I + C_L \quad (3.19)$$

3.1.3.2 Annual Cost Equations

Capital costs must be annualized and normalized by yearly desalinated water output to estimate the cost of water production at each site. The equations below detail the amortization of capital costs, which are combined with O&M costs to calculate the total annual cost of operation for the facility (c_T).

c_{DS} : Debt service [$\frac{\$}{year}$]

c_{Pi} : Piping O&M [$\frac{\$}{year}$]

c_{PS} : Pumping station O&M [$\frac{\$}{year}$]

c_{RO} : Desalination plant O&M [$\frac{\$}{year}$]

c_T : Total annual costs [$\frac{\$}{year}$]

c_{well} : Well cost O&M [$\frac{\$}{year}$]

$c_{W/PV}$: Installation O&M of either wind or solar [$\frac{\$}{year}$]

k_{RO} : Desalination plant O&M rate [$\$0.14/m^3$]

$k_{W/PV}$: O&M rate of either wind or solar, $f(P_{W/PV})$ [$\$/W$]

r_{Pi} : Piping O&M rate [1%]

r_{PS} : Pumping station O&M rate [3%]

r_{well} : Well O&M rate [1%]

t_A : Amortization period [20 years]

c_{BE} : Break-even cost of water [\$/kgal]

$$c_{DS} = C_T \frac{r_I \times (1 + r_I)^{t_A}}{(1 + r_I)^{t_A} - 1} \quad (3.20)$$

$$c_{PS} = C_{PS} \times r_{PS} \quad (3.21)$$

$$c_{Pi} = C_{Pi} \times r_{Pi} \quad (3.22)$$

$$c_{well} = C_{well} \times r_{well} \quad (3.23)$$

$$c_{RO} = k_{RO} \times Q_{cap} \times 365 \left[\frac{days}{year} \right] \times 3785 \left[\frac{m^3}{Mgal} \right] \quad (3.24)$$

$$c_{W/PV} = k_{W/PV} \times P_{W/PV} \quad (3.25)$$

$$c_T = c_{RO} + c_{Pi} + c_{well} + c_{PS} + c_{W/PV} + c_{DS} \quad (3.26)$$

$$c_{BE} = \frac{c_T}{Q_{cap} \times 365 \left[\frac{days}{year} \right]} \times \frac{1}{1000} \left[\frac{Mgal}{kgal} \right] \quad (3.27)$$

3.2 Results and Discussion

3.2.1 Geographically-Varying Water Production Costs

The significant geographic variance in brackish groundwater quality, renewable energy availability, and proximity to infrastructure results in a wide range of water production costs for potential desalination projects on all 1,445 GLO sites across Texas. As shown in Figure 3.5, the baseline cost of desalination for a 1 MGD desalination project powered by wind energy ranges from \$2.61/kgal to \$6.93/kgal depending on the location of the site. Concentrated brine produced as a byproduct of the desalination process must be disposed of and will incur costs not factored into the baseline costs. To account for the cost of disposal, it was assumed that a salt water injection (SWI) well must be drilled for each potential project at a cost of \$3 million. Applying this additional capital cost resulted in a \$0.80/kgal increase in water production cost for all potential projects, as can be seen in the *+ Disposal* column of Figure 3.5. Adding disposal costs yields a \$5.01/kgal average cost for wind-based desalination. In some cases, if the volume and salinity of brine is low enough, brine can be safely discharged to a nearby body of water, which virtually eliminates the cost of disposal. Another option could be to process brine to extract valuable minerals [63]. This option would likely increase the capital cost of potential projects, but would add another source of revenue.

In comparison to water production costs for solar-powered desalination projects, water costs for wind-powered projects are generally lower and vary less across the state. Figure 3.6 shows how solar-based desalination is \$0.16 to \$1.12/kgal more expensive than wind-based desalination, with an average baseline water cost of \$4.25/kgal. Although wind capacity is more expensive to install on a dollar-per-kilowatt basis than solar PV capacity (\$2,346/kW versus \$2,025/kW at utility scale) at the time of this writing [3], the higher capacity factors for wind across much of the state often make

it the lower cost option for powering a desalination plant. It is important to note that installation costs used in this study are estimates from NREL as a first test of economic viability. Future work needs to account for variation in local installation costs and capital costs, which are dropping with time. As with wind projects, brine disposal adds \$0.80/kgal to the water production cost for solar-based desalination, bringing the average cost to \$5.05/kgal. The calculated costs including disposal are considered the final water production cost estimates in the following discussion and selection processes.

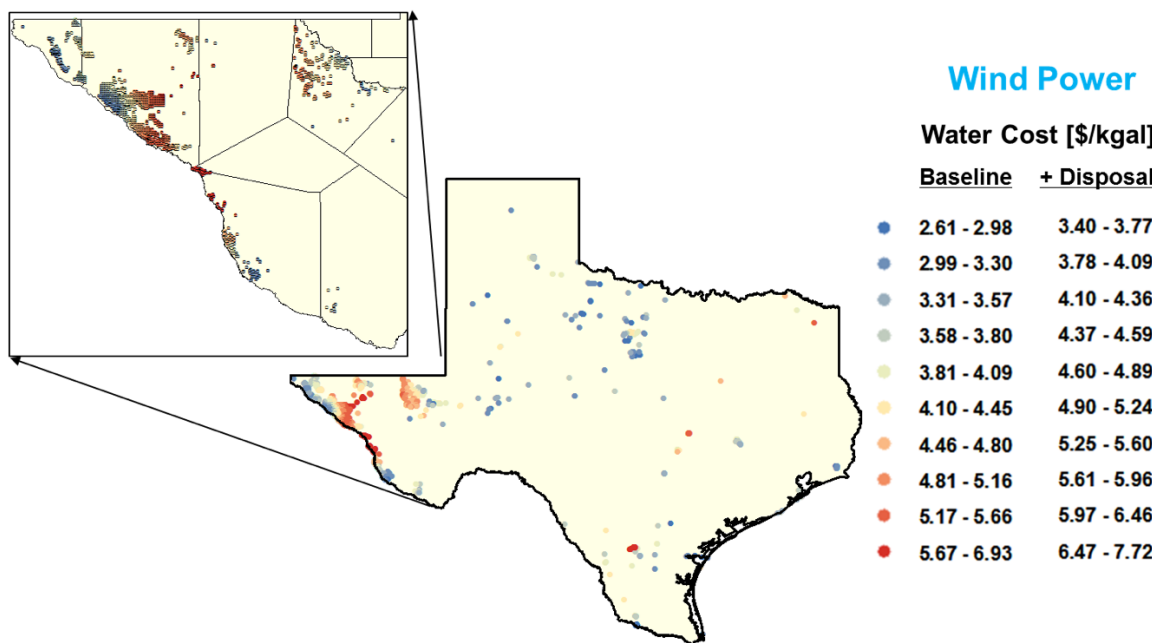


Figure 3.5: Geographically-varying water production costs for wind-powered 1 MGD desalination projects on Texas GLO sites. The Baseline column reflects water costs without disposal of brine, while the + Disposal column includes the cost of disposal via construction of an injection well. Inset shows expanded view of the West Texas region where there is a high density of GLO-owned land. Each dot represents potential water cost at an individual GLO site, but does not reflect the actual area of the GLO site.

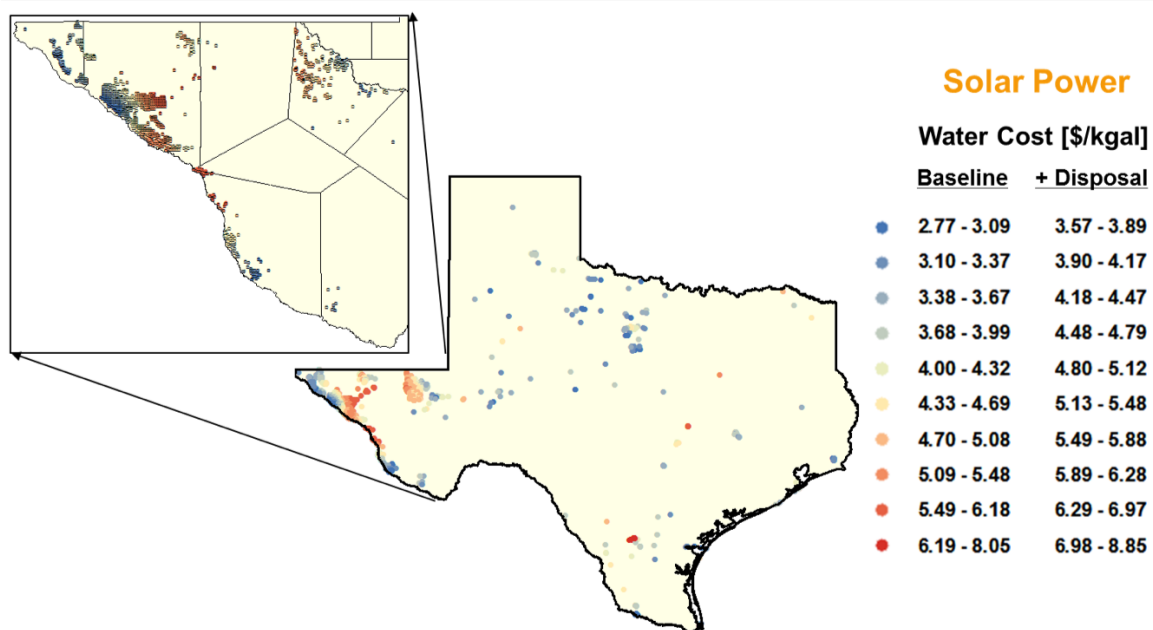


Figure 3.6: Geographically-varying water production costs for solar-powered 1 MGD desalination projects on Texas GLO sites. The Baseline column reflects water costs without disposal of brine, while the + Disposal column includes the cost of disposal via construction of an injection well. Inset shows expanded view of the West Texas region where there is a high density of GLO-owned land. Each dot represents potential water cost at an individual GLO site, but does not reflect the actual area of the GLO site.

3.2.2 Selection of Economically Viable Sites

The most economically viable sites for potential desalination projects were selected by comparing the estimated water production costs to local municipal water prices, which can vary widely [60]. The calculated solar and wind-powered desalination costs (including brine disposal) at each GLO site were compared to the local municipal water prices shown in Figure 3.2. GLO sites were removed if their desalination cost was higher than the local municipal water price. This down-selection process reduced the number of potential desalination projects to 193 potentially economically

viable sites, as shown in Figure 3.7 and Figure 3.8. Municipal water prices do not wholly reflect the cost of sourcing and treating water, and will be higher than the actual cost of water production. Therefore, local municipal water prices can be considered the rate at which potential desalination projects could be contracted to supply water. If the cost of water production at a wind or solar powered desalination facility is not lower than potential water contract rates, then it is unlikely that facility would be economically viable. The number of viable sites could be downselected further by comparing desalination costs to the existing cost of municipal water production, which could be considerably lower than the rates at which that water is sold. Many municipalities have not invested in recent water infrastructure projects, so water production costs would likely only include operational and maintenance costs. Due to the variability in water pricing structures future work should include a detailed comparison of the estimated water production costs with local municipal prices, including both fixed and variable costs.

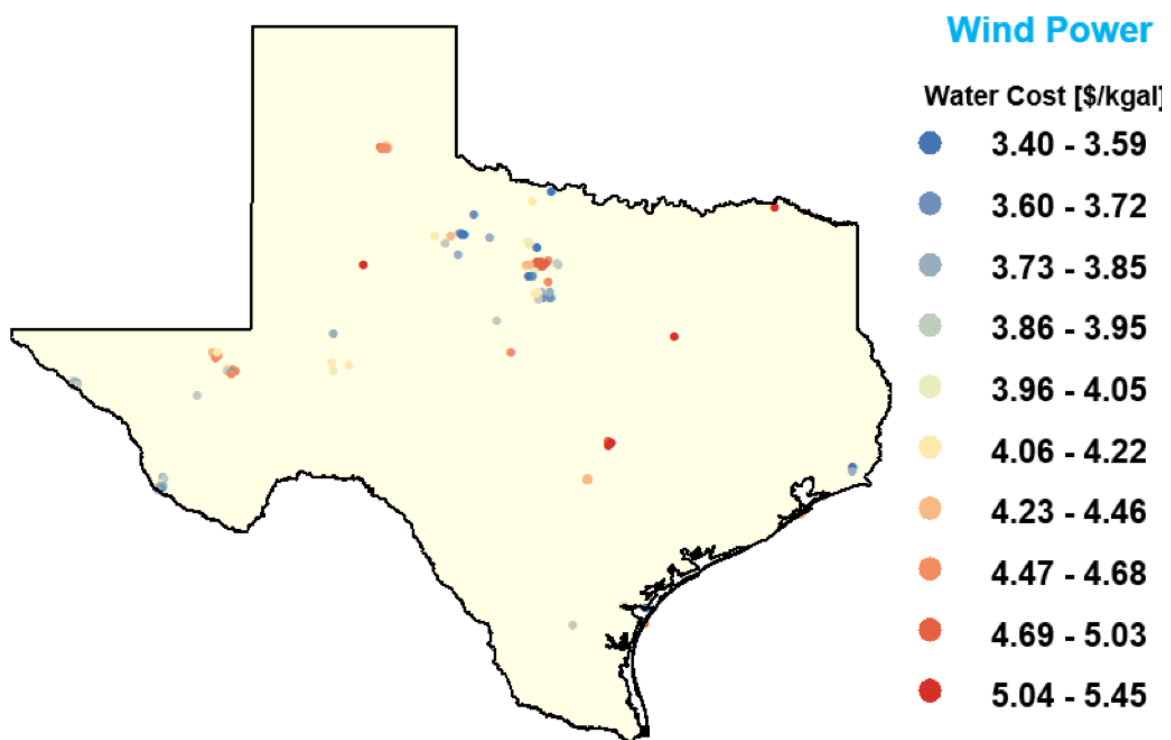


Figure 3.7: Water costs for wind-powered 1 MGD desalination projects at the most economically viable GLO sites in Texas. These sites were selected by removing potential sites where the estimated water cost is higher than local municipal water rates.

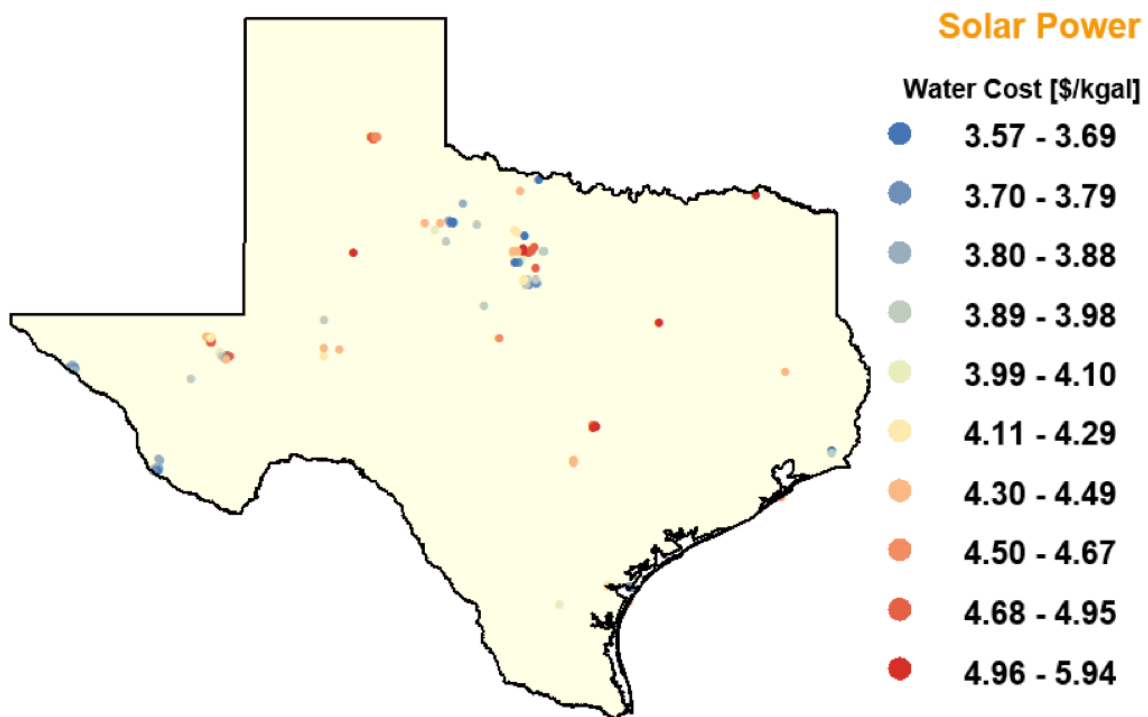


Figure 3.8: Water costs for solar-powered 1 MGD desalination projects at the most economically viable GLO sites in Texas. These sites were selected by removing potential sites where the estimated water cost is higher than local municipal water rates.

The estimated desalination costs were compared at each of the down-selected GLO sites to determine if wind or solar was economically preferable at a given location. The results of this comparison show that using wind to power a desalination facility is economically preferable at 145 of the 193 sites; solar was preferable at the remaining 48 sites. Solar and wind resources are both abundant in Texas; however, the particularly high capacity factors for wind across much of the state helps wind deliver the lowest cost electricity. Costs are generally lowest in northern Texas where wind is abundant and brackish groundwater characteristics make the specific energy required for desalination relatively low. However, variations in local groundwater quality and

distance to available water infrastructure can still cause desalination costs to vary considerably within the region. The lowest desalination cost (\$3.40/kgal) is calculated for a wind-powered project just north of Wichita Falls, a potential market for the produced water. Solar energy is generally the more viable energy option in two clusters of GLO land located in Hudspeth and Presidio counties near the Texas-Mexico border. Solar capacity factors are highest in this region while the lack of wind in the low-lying area along the Rio Grande (the southern border river between Texas and Mexico) make employing wind turbines less appealing. The average desalination cost for the 48 sites where solar energy is the lower-cost option is \$3.89/kgal while the average cost is \$4.24/kgal for the remaining 145 down-selected sites where wind is more economically viable. Despite the appearance of solar being cheaper than wind at these down-selected sites, the average desalination cost of wind-powered projects across all 1,445 GLO sites is actually lower than that of solar-powered projects. These results are summarized in Table 3.2.

Table 3.2: Summary of the cost to desalinate brackish groundwater using co-located solar or wind power facilities. Figures reflect water production costs during the amortization period of potential projects. The minimum, maximum, mean, and median costs are shown for both wind and solar powered facilities. For the down-selected sites for economic viability, the renewable energy type reflects the cheapest option at a given site.

	Renewable Energy Type	Min. Desal. Cost [\$ /kgal]	Max. Desal. Cost [\$ /kgal]	Mean Desal. Cost [\$ /kgal]	Med. Desal. Cost [\$ /kgal]	Number of Sites
All GLO Sites	Solar	3.57	8.85	5.05	4.89	1445
	Wind	3.40	7.72	5.01	4.85	1445
Down-Selected Sites	Solar	3.66	5.35	3.89	3.82	48
	Wind	3.40	5.45	4.24	4.32	145

The estimated desalination costs for the 193 down-selected sites are competitive with local municipal water prices. However, the estimated costs are higher than many existing wholesale water prices because many wholesale suppliers of water are not financing new projects. For example, the Lower Colorado River Authority supplies water at a rate of \$0.45/kgal [64]. Compared to the \$713 per acre-ft (\$2.16/kgal) brackish groundwater desalination cost estimated by the 2017 State Water Plan, the water costs calculated in this study are higher. The price of \$2.16/kgal is \$1.24/kgal below the lowest calculated cost because the state water plan provides estimates for projects ready by 2070, including costs for projects beyond their amortization period [30]. Water costs during amortization for conventional brackish groundwater desalination plants range from \$2.54/kgal to \$10.76/kgal as outlined by the 2016 Water Plan for Region F, which includes much of West Texas [65]. All of the water costs calculated in this study fall within this range.

In addition to supporting municipal needs, it might also be possible to sell treated water to oil and gas operators. Many oil and gas operators are located on or near GLO sites and pay considerably higher rates for the water used in their extraction operations. In 2014, the average cost of water for oil and gas operations was greater than \$9.00/kgal in twenty Texas counties, with operators in Scurry County paying over \$25/kgal [37]. The highest desalination cost calculated in this study is less than half this rate. An added benefit of selling to the oil and gas industry is that the brackish groundwater would not need to be treated to drinking standards, thereby lowering the energy intensity and cost of desalination. Ongoing research efforts seek to utilize saline water for hydraulic fracturing [66], so brackish groundwater may only need to be pumped to the surface without further RO treatment. For the 1445 sites analyzed here, the RO facility accounted for 80% of power demands on average, with the remaining 20% required for pumping water to the surface. The average

combined cost of the RO facility and saltwater injection brine disposal well accounted for 40% of capital water infrastructure costs. Removing the need for RO desalination from potential projects would significantly reduce the cost of producing water for customers such as oil and natural gas drilling operators. Further, by utilizing brackish groundwater, competition for local freshwater might be reduced.

The water production costs found here are generally lower than those calculated in previous studies examining desalination processes powered by renewable energy. The lowest water costs detailed by Al-Karaghoul and Kazmerski for RO desalination of brackish water are \$24.61/kgal and \$7.38/kgal when powered by solar PV and wind respectively [39]. The wind-powered desalination cost from previous work is comparable to the higher end of water production costs calculated here. However, the highest water cost estimated in this study is still less than half the lowest figure presented by Karaghoul and Kazmerski for PV-powered RO desalination. One potential reason for the discrepancy in costs is the variance in local renewable energy availability. The availability of solar and wind resources might be greater for many of the sites examined in Texas than in the regions where previous studies were conducted. Furthermore, the cost of solar PV and wind turbines has decreased since the publication of the referenced work [2, 3]. The most significant difference between this study and previous work is the capacity of desalination facilities considered. The 1 MGD RO facility analyzed here is approximately four times larger than the wind-powered RO facility and more than forty times larger than the solar-powered RO facility discussed by Karaghoul and Kazmerski. The cost of desalinating water decreases considerably with increasing RO facility capacity, as is discussed in the following section.

3.2.3 Increasing Facility Capacity

The majority of analysis within this study focused on a 1 MGD desalination facility with relatively low upfront capital requirements and power demands from renewable energy sources. However, a larger plant might desalinate water at a lower cost due to economies of scale. To investigate the effect of increasing the capacity of the desalination plant, estimates were made for a 3 MGD brackish groundwater desalination plant by averaging the performance characteristics of the 48 solar-powered and 145 wind-powered sites that were previously down-selected. The results shown in Table 3.3 show how tripling the size of the plant reduced the estimated desalination cost of solar and wind-powered plants by 19% and 23%, respectively. The 1 MGD results in Table 3.3 differ slightly from the down-selected averaged results in Table 3.2 due to rounding errors incurred by inputting averaged parameter values to the costing model for the results presented in Table 3.3. The reduction in cost by scaling up the desalination plant capacity demonstrates the improved economic potential of a larger-scale desalination facility powered with renewable energy. However, there are still technical limits that must be considered. Not all brackish aquifers will be productive enough to supply larger facilities, particularly if brackish groundwater is being withdrawn by other facilities within the same area. Additionally, if the desalination and renewable energy plants are to be collocated, fewer plots of GLO land will be large enough to cover their combined footprint.

Table 3.3: Calculated desalination costs for hypothetical 1 MGD and 3 MGD brackish groundwater desalination facilities. To estimate the price of water from a 3 MGD desalination facility the characteristics of the down-selected sites were averaged for solar and wind, respectively. The averaged site and well parameters were then used in the costing model to estimate the price to desalinate brackish groundwater at a 3 MGD facility.

Desalination Capacity	Desalination Cost [\$/kgal]	
	1 MGD	3 MGD
Solar	3.87	3.14
Wind	4.17	3.21

3.2.4 Considering Water Scarcity

The 2017 State Water Plan predicts an annual water need of 4.8 million acre-ft for all of Texas by the year 2020 [30]. As shown in Figure 10, projected water needs vary significantly across the state. Local water needs can be used as alternative metric, rather than only comparing to local municipal water prices. Municipal water rates do not necessarily reflect water scarcity and demand in an area, so there might be areas where the future need for additional water sources outweighs the higher cost of desalinating brackish groundwater.

Solar and wind-based desalination costs were selected for each GLO site depending on the lower value and plotted in Figure 10 without filtering sites based on municipal water rates. Under this analysis method, the most viable sites are where estimated water costs are relatively low while the surrounding county is projected to have a high water need. El Paso County is a particularly promising area for development of both wind and solar-powered brackish groundwater desalination plants. Many of the potential projects in this region have relatively low water production costs (\$3.80/kgal - \$4.17/kgal) while the countys projected 2020 annual water need is the eighth-highest in the state (143.4 billion gallons). El Paso, a city with a growing

population of over 650,000 people, presents a major market for desalinated brackish groundwater. Additionally, data from the conventionally-powered Kay Bailey Hutchison 12.5 MGD desalination plant located in El Paso can provide more accurate data on the energetic and economic cost of desalinating brackish groundwater in the area [67]. The number of proposed projects in El Paso County highlights the potential for development in this region [68].

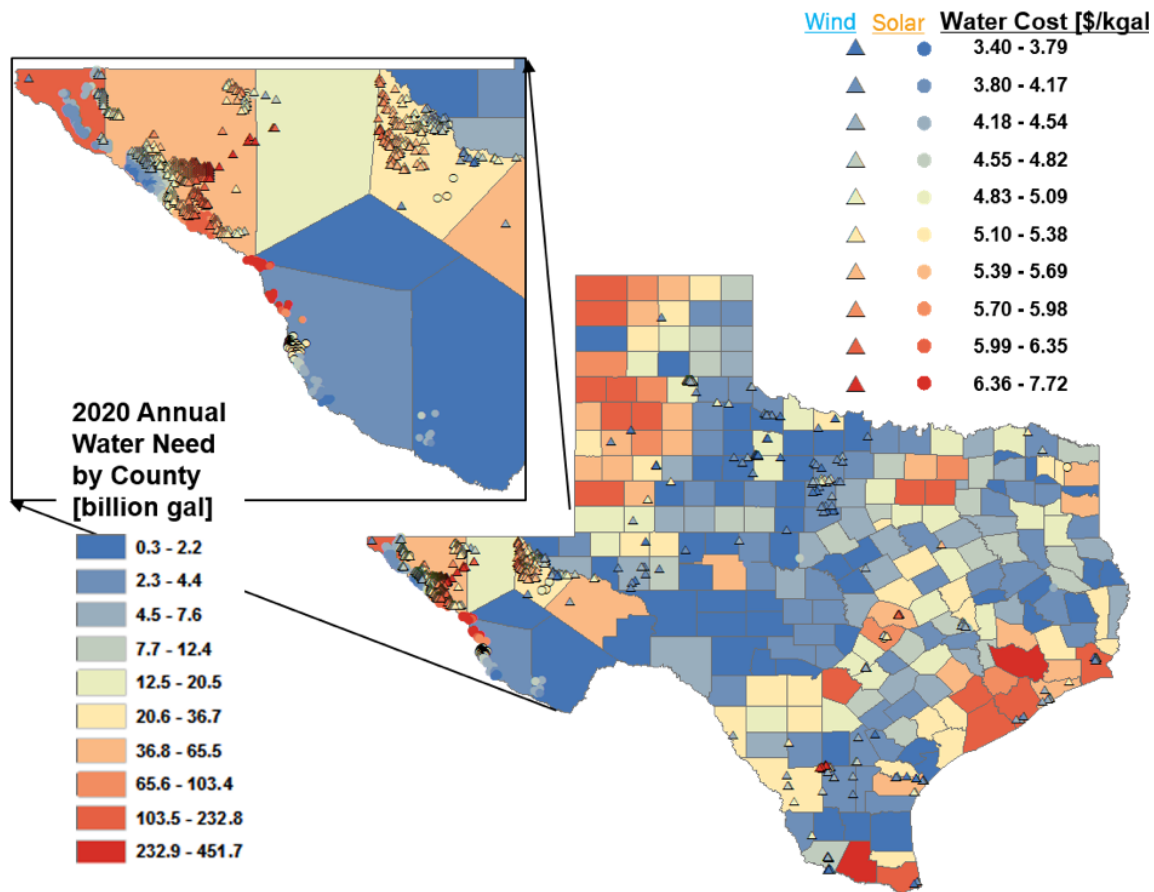


Figure 3.9: Water costs for wind and solar-powered 1 MGD desalination projects on all 1445 potential Texas GLO sites. Sites where solar energy is the cheaper option are shown as circles, while sites where wind is cheaper are displayed as triangles. Texas counties are color coded based on their projected annual water need for the year 2020 as estimated by the 2017 Texas State Water Plan.

3.3 Conclusions

The work in this chapter developed a novel multi-layered spatial model that integrates different elements of techno-economic performance factors to estimate viability of desalination powered by wind and solar energy. To illustrate the method, the characteristics of 1,445 sites in Texas were assessed. It was determined that 193 of these sites might be technically and economically viable to implement renewably powered brackish groundwater desalination facilities. At 145 of the 193 potential sites, the cost of desalinating brackish groundwater is lower when the facility is powered using wind turbines rather than employing solar arrays. The economic advantage of wind power stems from relatively high capacity factors for wind power generation across much of Texas. The lowest estimated marginal cost for brackish groundwater desalination is \$3.40 per thousand gallons (kgal), which is for a wind-powered project just north of Wichita Falls, a potential market for the produced water. Costs are generally lowest in north Texas where wind is abundant; however, local groundwater quality and distance to available water infrastructure can cause costs to vary considerably. Due to the abundance of solar energy and relative lack of reliable wind in far west Texas, solar energy is more viable in two clusters of GLO land located in Hudspeth and Presidio counties near the Texas-Mexico border.

The results of this analysis indicate that integrating renewable energy for brackish groundwater desalination is not only technically and economically viable but might also generate revenue for the state of Texas, increase local water supply, and offer a service compatible with intermittent availability of wind and solar power. If the prices for wind and solar energy continue to drop, and if prevailing water prices continue to rise, then even more sites will be viable.

The methods detailed here can be applied to estimate the economic and tech-

nical viability of desalinating brackish groundwater with renewable energy in regions with brackish groundwater aquifers beyond the state of Texas. Planners and other entities may use this framework to site desalination facilities and/or ascertain the viability of desalination powered by renewables within a given region.

Chapter 4

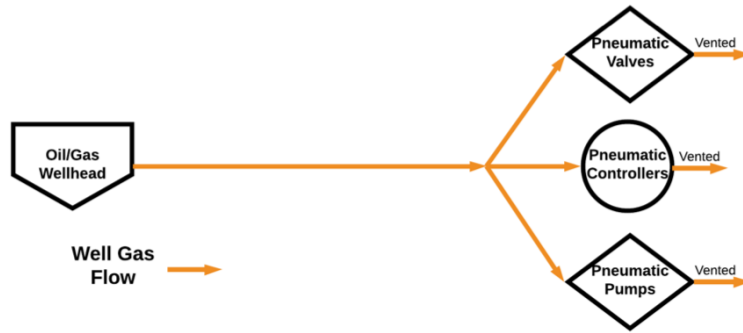
Assessing the Technical and Economic Viability of Using Variable Renewable Energy to Power Electrified Well Site Pneumatic Systems

4.1 Methods

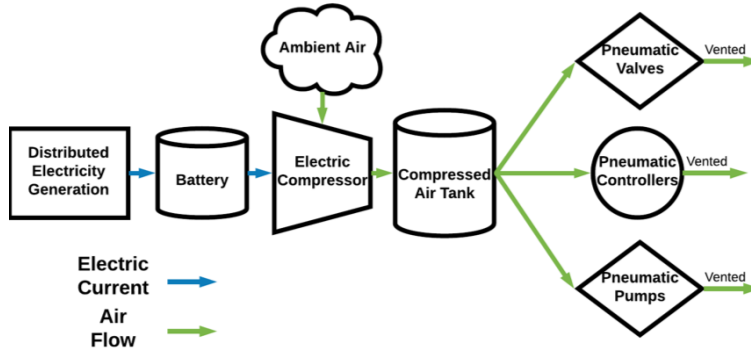
4.1.1 Potential configurations of electrified well site systems

Under this study, two different strategies were considered for replacing pneumatic systems powered by well gas. One option is to exchange all components—controllers, actuators and pumps—to equipment that is directly powered by electricity. This scheme is referred to as the electric configuration. The second option, referred to as the electro-pneumatic configuration, is to retain the pneumatic system, but power its components with instrument air, which is ambient air that has been compressed by an electrically-driven compressor. This option thus replaces the emission of methane with ambient air. A simplified diagram of these configurations and their energy flows are shown in Figure 4.1.

Pneumatic Configuration



Electro-pneumatic Configuration



Electric Configuration

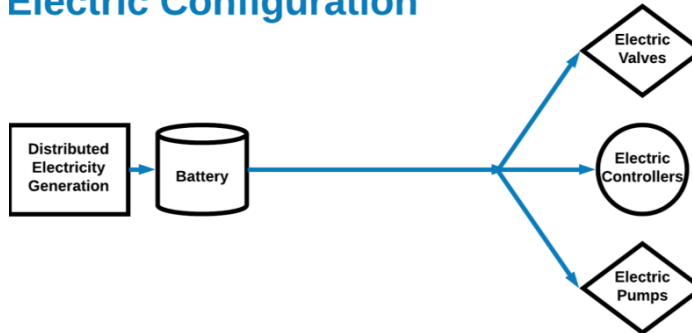


Figure 4.1: Diagrams of the electric and electro-pneumatic configurations analyzed as potential options for electrifying conventional pneumatic well site systems. The Pneumatic and Electro-pneumatic systems both vent gas to the atmosphere. However, the Electro-pneumatic system vents ambient air instead of methane. The Electric configuration replaces the pneumatic valves, controllers and pumps with electric components, thereby making the electric compressor and compressed air tank unnecessary. Electricity can be generated from distributed resources such as solar, wind and geothermal energy.

There are advantages and drawbacks to each configuration. Electric components generally have low power loads, but have historically been less reliable than conventional pneumatic equivalents due to the limited lifetimes of electric actuators. The reduced reliability has slowed their adoption over concerns about maintenance costs and costly downtime [28]. By comparison to the electric configuration, the electro-pneumatic configuration could require higher power demands but may require lower installation cost due to reuse of existing pneumatic components if implemented as a retrofit. The use of compressed air also provides the option of storing energy as compressed air in addition to or instead of electrochemical batteries to store electricity.

4.1.2 Development of well site power load demand tool

One of the primary objectives of this dissertation is to develop an interactive Excel-based tool for simulating the power requirements for the controllers in question. The energy simulator can serve as a screening tool for well site operators to determine the temporally-varying power demands incurred by switching a standard pneumatic system to either an electrified or electro-pneumatic system. To capture the significant site-to-site variation in equipment inventories and power demands, the tool is equipped with an extensive set of user inputs. These inputs are integrated into the user interface of the tool as shown in Figure 4.2.

The user will first enter the number of pneumatic valve actuators and chemical pumps operated at a given site under the “Parameters“ section of the userform. The user then enters the site’s ambient air temperature and the supply pressure of compressed air needed in the electro-pneumatic configuration. Typically this will be the pressure of well gas already supplied the pneumatic system. The electric configuration will be equipped with electric controllers. However, there will be an option for the

type of controllers used in the electro-pneumatic scheme. There are a variety of pneumatic controllers employed at oil and gas wells which will bleed supply gas at varying rates. These are categorized as options under the “Controller Type” input. There is also the option to integrate electric controllers (as in the electric configuration) into the electro-pneumatic configuration. High-bleed controllers continuously consume a considerable amount of supply gas, so an operator may opt to replace controllers but retain pneumatic pumps and actuators. The pump parameters will vary depending on the process they are used for, and will affect the power draw under the electro-pneumatic configuration. Pumps may be operated continuously or intermittently, as indicated in the “Scheduling” section. If pumps are operated intermittently, the user specifies how many times a day the pump is powered and how long it is typically run for each time. The “Delay” input is used to indicate the time at which the pump is first powered on a given day. The tool then automatically schedules the operation of each pump throughout the day by allotting an equal downtime period between each period of activation. Valve actuators are only powered intermittently, and are given the same scheduling inputs as intermittently-operated pumps. The scheduling inputs are key to calculation of temporally-resolved power loads.

4.1.2.1 Calculation of instantaneous power loads

Once the required parameters have been entered into the energy load tool, time-varying power loads for both the electric and electro-pneumatic systems are evaluated for one day of operation. The scheduling inputs parameterize binary powered/rest variables for each pump or actuator at discrete time intervals. The tool can calculate the total power load for every second throughout the day of evaluation. For the electric configuration, the electrical power draw from each component will be acquired from specification sheets for the models of electrical controllers, actuators,

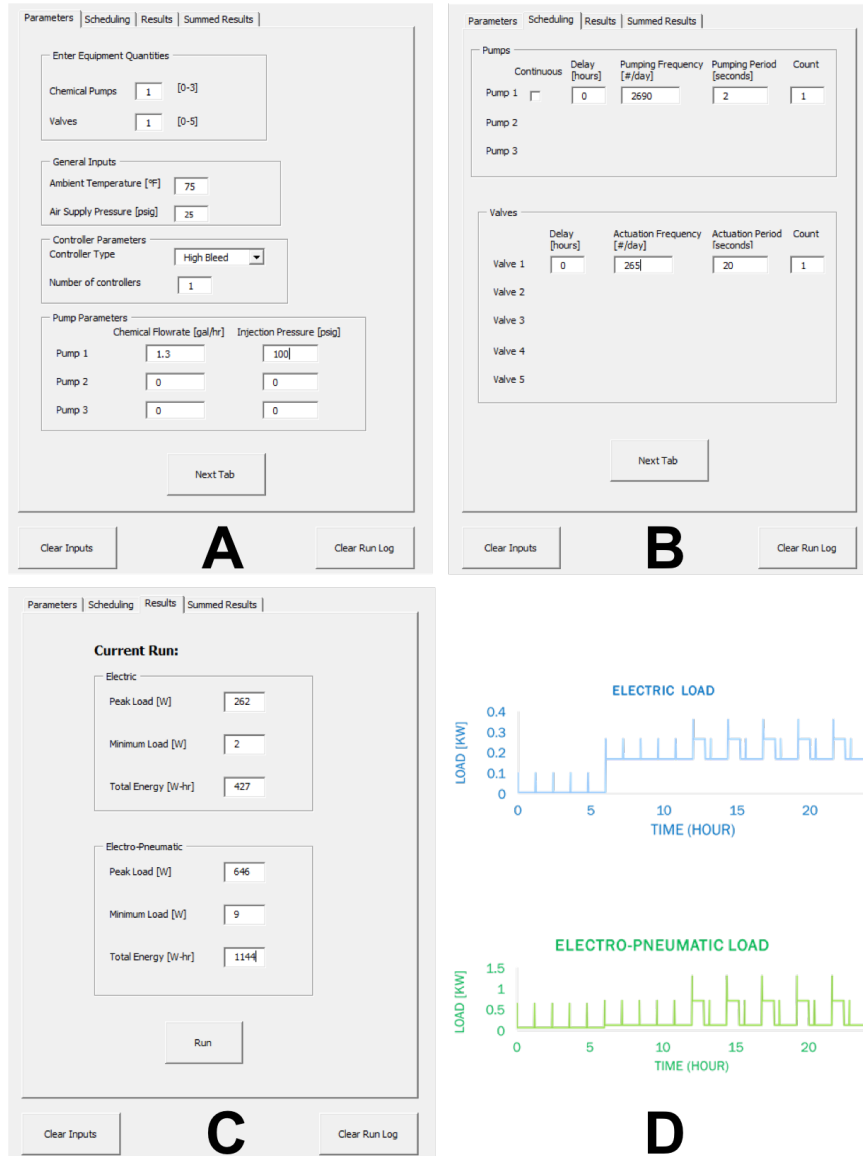


Figure 4.2: Screenshot of the user form used to enter site-specific parameters into the energy simulator. The “Parameters” tab shown in (A) is used to initialize an inventory of equipment and enter equipment-specific parameters. The “Scheduling” tab shown in (B). Summarized power load results are displayed in the Results tab shown in (C). Sample outputs of one-day power loads produced by the energy simulator are shown in (D). The power loads shown here are not representative of the actual well site power load examined in this study. Actual power loads fluctuate much more frequently, so these load profiles are presented for illustrative purposes.

and chemical pumps most commonly utilized at oil and gas production sites. Data for these components is sparse so they are assumed to operate at maximum power when in the powered state. Controllers are be constantly powered since they must be able to detect system parameters and relay signals at all times. The total power load for the electric system E_t at time step t can be described by the following expression.

$$P_e^t = \sum_{c=1}^n p_c^t \quad (4.1)$$

Here p_c^t represents the binarily-varying power load for component c at time t . Electric wellsite equipment is generally powered with direct current, so the total power load can be calculated as the sum of the power draw from each component.

The power load of the electro-pneumatic configuration is drawn by the electrically-driven compressor supplying instrument air to the pneumatic controllers, actuators, and pumps. These components each require a set pressure and flowrate of air when powered, and can also bleed air while at rest. By performing a thermodynamic analysis on an adiabatic compressor, the electric power required for compression can be expressed as

$$P_p^t = M^t \times \frac{h_{out,s} - h_{in}}{\eta_i \times \eta_e} = \left(\sum_{c=1}^n m_c^t \right) \times \frac{h_{out,s} - h_{in}}{\eta_i \times \eta_e} \quad (4.2)$$

where

m_c^t : binarily-varying air mass flow rate drawn by component c at time t [kg/s]

h_{in} : specific enthalpy of air entering the compressor [kJ/kg]

$h_{out,s}$: specific enthalpy of air exiting the compressor assuming isentropic compression [kJ/kg]

η_i : isentropic efficiency of the compressor [%]

η_e : conversion efficiency of the electric driver from electrical to mechanical power [%]

Compressor and driver efficiencies are taken from data tables available in the OPGEE [29]. By approximating air as an ideal gas, the inlet enthalpy h_{in} can be interpolated from tabulated material properties as a function of ambient temperature. The isentropic outlet enthalpy $h_{out,s}$ can similarly be determined as a function of the inlet (ambient) air pressure and the outlet pressure required by the pneumatic system. Well site pneumatic systems generally do not utilize gas pressurized beyond 100 psi, so the ideal gas assumption does not create significant calculation error. These systems generally utilize gas pressurized within 20 to 30 psi, and all components are assumed to be calibrated to the same supply pressure. However, the required pressure will vary from site to site, so it is included as an input to the energy calculator. Air flowrates for all components were acquired from specification sheets for the most commonly used makes of controllers, chemical pumps, and valve actuator positioners.

4.1.3 Modeling variable power resources and loads with energy storage

The key challenge associated with solar or wind-based electricity generation is the transient availability. Variable power generation must be coupled with energy storage to ensure reliable operation of well site power loads. To assess the viability of powering well sites with temporally varying power generation under varying generation and storage capacities we utilized a time series energy flow model described in Figure 4.3. At every time step t , the model determines whether there is sufficient energy generated (E_{gen}^t) during the time interval and available in storage (E_{store}^t) to meet the required load (E_{load}^t). Energy flows are evaluated at time intervals (t) of one second due to the high frequency of component activations. The equations describing these energy flows depend on the configuration and are detailed in Equations 4.4-4.6

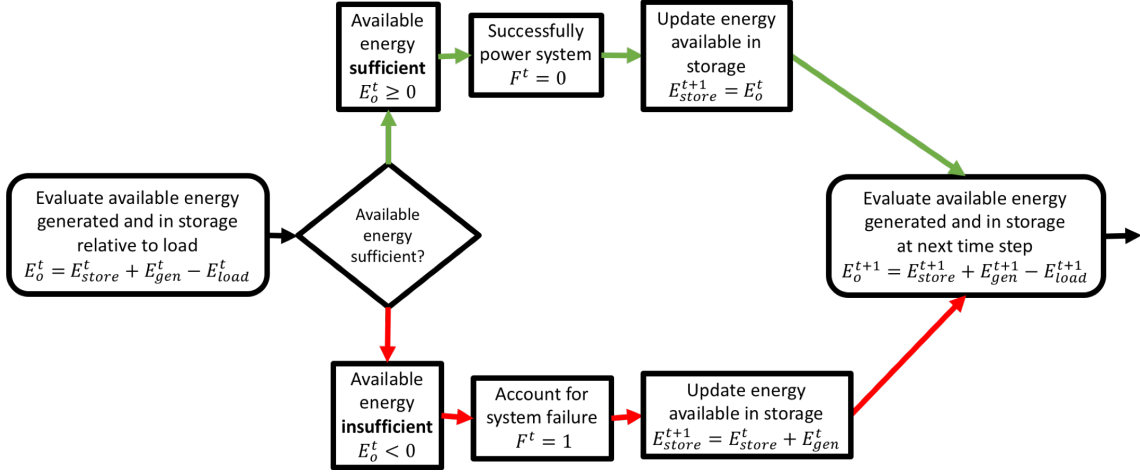


Figure 4.3: Decision process used to model energy available to power variable loads and charge energy storage at every time step within a given period of evaluation.

and 4.9-4.12. If there is sufficient energy to meet the load, then the model updates the net energy taken from or added to storage and continues to the next step. If the energy load cannot be met, then the model tracks a system failure ($F^t = 1$) at that time step and applies a cost of failure ($C_F^t = c_o$). The stored energy is then updated to reflect the energy added without energy being withdrawn.

Generated energy will depend on the time-varying resource availability (solar insolation) and is limited by the installed generation capacity (PV array size). It was assumed that energy is stored as electricity in lead-acid electrochemical batteries and is limited by the size of the battery bank. When considering an electro-pneumatic configuration, the model is modified to also consider energy stored as compressed air in tanks. Tracking system failures is essential to determining the reliability of the system. Here we assess reliability as the percent of time during an evaluation period that the system is able to successfully meet the required load. System reliability R is calculated over T total time steps as described in Equation 4.3. $F^t = 0$ when energy is available to meet the required energy load and $F^t = 1$ when available energy is

insufficient.

$$R = 1 - \frac{\sum_{t=1}^T F^t}{T} \quad (4.3)$$

4.1.3.1 Electric Configuration

A fully electric well site control system was modeled with PV power generation and electric batteries for energy storage as shown in Figure 4.1. The time-varying energy flows under the electric configuration depend on installed PV capacity (K_{PV}), battery capacity (K_B), transient capacity factors (CF_{PV}^t) and power loads (P_e^t) as described by Equations 4.4 - 4.6.

$$E_{gen, e}^t = K_{PV} \times CF_{PV}^t \times \eta_c \times \Delta t \quad (4.4)$$

$$E_{load, e}^t = P_e^t \times \Delta t \quad (4.5)$$

$$d_{lim} \times K_B \leq E_{store, e}^t \leq K_B \quad (4.6)$$

Battery charging and electrical losses are accounted for by the charging efficiency factor η_c , which is assumed to be 90% [3]. The discharge limit d_{lim} limits the extent to which the battery can be depleted to avoid harming battery performance and is assumed to be 30%.

System reliability and costs were evaluated for 15 years of operation at a new well site with varying amounts of installed PV and battery capacity. The cost of avoided methane emissions when utilizing the electric system ($\bar{C}_E$) is described by Equation 4.7. Costs included variable capital for PV arrays and lead-acids batteries

(C_{PV}, C_B) supplied by NREL reports [3], as well as the fixed cost of procuring and installing electric controllers, valve actuators, a control panel and chemical pumps ($C_{cont,e}$) which were taken from a report produced by the Carbon Limits consulting group [52]. Installation costs were factored in as 20% of equipment capital. Operation and maintenance cost (C_{OM}) included yearly maintenance of all system components and replacement of batteries every five years. These variables and others discussed in this analysis are detailed in Table 4.2.

To fairly evaluate the cost of methane abatement, the total costs of a baseline pneumatic system (C_{base}) were subtracted from the lifetime costs of the solar-powered electric system being examined. The baseline costs include capital and maintenance costs for a pneumatic controller, valve, and chemical pump powered by well gas. To arrive at the cost of avoided methane, the present value of the offset costs of the electric system were then divided by the total mass of methane that would be emitted by the standard pneumatic system operated with well gas (M_{CH_4}) as shown in Equation 4.7. Present value was calculated based on costs incurred each year in the 15 year period with a discount rate of 7%. The cost of failure in this configuration ($C_{F,E}^t$) was factored in as the loss of revenue resulting from periods of system failure. The electric configuration was assumed to be operated without a back-up system, so a worst-case scenario was considered where the well would not be able to produce natural gas while power loads could not be met by the PV/battery system. Equation 4.8 describes how $C_{F,E}^t$ is calculated as the product of natural gas price (C_{HH}) and the volume of natural gas produced by the well during a time step ($\dot{V}_{well}$). Lost revenue cost was based on 1 MMScf/day production of natural gas [69] and the March 2018 Henry Hub price of \$2.69/MMBtu [70]. The value of natural gas that could be captured and sold by utilizing an electrified system that would otherwise be vented by a conventional pneumatic control system was not included in the cost analysis.

In some scenarios, including the value of captured natural gas as a revenue stream could potentially result a net profit over the lifetime of the well if capital expenses for methane abatement are low and captured natural gas can be sold at a high prices. However, the focus of this analysis is to identify the *cost* of methane abatement by electrifying pneumatic systems with renewable energy as opposed to an accounting of net profit or net loss. Furthermore, reduced venting of natural gas at oil wells in predominantly oil-producing regions does not necessarily result in a greater revenue stream as the absence of natural gas transmissions infrastructure might preclude sales of captured natural gas.

$$\bar{C}_E = \frac{PVal(C_{PV} + C_B + C_{cont,e} + C_{OM} + \sum_{t=1}^T C_{F,E}^t - C_{base})}{M_{CH_4}} \quad (4.7)$$

$$C_{F,E}^t = c_{HH} \times \dot{V}_{well} \quad (4.8)$$

4.1.3.2 Electro-Pneumatic Configuration

Simulating the electro-pneumatic system required a separate model where energy flows were monitored in the form of electricity as well as compressed air. Electricity is generated by the PV array, stored in a battery, and utilized by an air compressor. The compressed air is stored in a storage tank and utilized by conventional pneumatic equipment as shown in Figure 4.1. The equations governing the flow of energy from PV generation to the electric batteries and compressor were modeled as described above. However, a thermodynamic analysis was applied to the flow of air from the compressor to compressed air storage tanks and pneumatic components. The energetic content of air flows was modeled with an ideal gas approximation to estimate the pressure of air in the compressed air storage tanks (p_{store}^t). The highest pressures

examined here are 200 psi. The compressibility factor of air ranges from 0.992 to 1.001 at temperatures of 0-100 °C at this pressure, so deviations from ideal conditions are negligible. Energy is modeled as a function of air mass flow rates supplied by the compressor (m_{supply}^t) and drawn by pneumatic components (m_{load}^t). Energetic flows of compressed air are modeled with Equations 4.9-4.12.

$$E_{gen,p}^t = m_{supply}^t \times h_{supply} \times \Delta t \quad (4.9)$$

$$E_{load,p}^t = m_{load}^t \times h_{store}^t \times \Delta t \quad (4.10)$$

$$p_{min} \leq p_{store}^t \leq p_{max} \quad (4.11)$$

$$p_{store}^t \sim \frac{E_{store,p}^t}{V_{tank}} \quad (4.12)$$

Utilizing an ideal gas approximation to model pneumatic energy allows specific enthalpies h to be determined as solely a function of temperature. Enthalpy of air entering the tank (h_{supply}) is evaluated at ambient temperature while enthalpy of air exiting the tank (h_{store}) is evaluated at the time-varying temperature of pressurized air in the tank. It also allows p_{store}^t to be calculated as a function of storage tank volume (V_{tank}) and temperature/energy content. The system must be able to supply the required gas flow rates at the necessary pressure. System failures occur when pressure in the compressed air storage tank (p_{store}^t) drops below that required by the pneumatic equipment (p_{min} assumed here to be 25 psi) and there is insufficient electrical energy available to the compressor for pressurization. The binary variable

m_{supply}^t is zero when the compressor is not utilized or a constant value when it is powered. The compressor can be operated whenever there is enough energy available to power the compressor over the given time interval, thereby maximizing the pressure of air in the tank and utilizing compressed air as the primary energy storage medium. However, compressed air systems are conventionally operated to maintain the minimum pressure required by the system, in which case electric batteries can charge more completely and serve as the primary energy storage medium for the systems considered here. Both modes of operation are examined in this study.

Electro-pneumatic systems can be backed up with existing well gas pressure, so the overall system could achieve 100% reliability, however utilizing well gas would once again emit methane. The cost of failure is therefore the penalty attached to emissions of methane resulting from switching to utilization of well gas. This penalty is factored in as a mass of methane emitted by the pneumatic system (m_P^t) that is subtracted from M_{CH_4} as shown in Equation 4.13. The cost of avoided methane emissions $\bar{C}_{EP}$ included present value of capital and O&M for PV arrays, inverters and lead-acids batteries as in the electric configuration. The cost of a procuring, installing and maintaining an air compressor (C_{AC}), air storage tanks (C_{ST}), and pneumatic controllers and pumps ($C_{cont,p}$) were also factored into the analysis [24, 52]. A five horsepower air compressor equipped with an air dryer was considered throughout this analysis since smaller compressors generally cannot operate reliably and must be replaced frequently [24, 52]. Here it is assumed the compressor must be replaced every five years as a maintenance cost. The cost of the compressed air tank depended on its volume and was taken from an EPA study [24].

$$\bar{C}_{EP} = \frac{PVal(C_{PV} + C_B + C_{OM} + C_{AC} + C_{ST} + C_{cont,p} - C_{base})}{M_{CH_4} - \sum_{t=1}^T m_P^t} \quad (4.13)$$

4.1.4 Well Site Pneumatic System Parameters

Within Texas or even within the Permian basin, the timing and magnitude of power loads differ from site to site as the inventory of equipment and productivity of wells can vary considerably. The system considered here is a simple, but relatively common inventory of equipment consisting of one valve actuator, one liquid level controller, and a single chemical pump as shown in Figure 2.3 that we assume to be consistent between the three locations examined in this study. The operational details of these components are described in Table 4.1. Pneumatic well site systems vary considerably from site to site and might include additional components. However, the system examined here can found at a considerable portion of unconventional wells and presents power loads that can be feasibly met with distributed power sources such as solar PV and energy storage.

Operational data for both the electric and electro-pneumatic components are sparse so we assumed that the components of both configurations operate at maximum power when in the powered state. Electrical loads fluctuate considerably throughout a day of operation as components are activated to facilitate well site processes. The timing of power draws were based on observations of individual natural gas wells at production sites in the Barnett shale region which were visited as part of this study during October of 2017. The frequency of valve actuator and chemical pump activations throughout a day of operation was also based on time-resolved emissions data collected by Allen et al [26]. A seven-minute sample of the electric power and compressed air loads is shown in Figure 4.4. Electric loads will also vary over the lifetime of the well as production volumes change. However, loads were assume to be consistent day to day for one year of simulated operation. Furthermore, the frequency of activations was assumed to be consistent over the lifetime of the well.

Table 4.1: Inventory of components and operational parameters for the pneumatic well site system considered throughout this study. The frequency of activations is assumed to be consistent over the lifetime of the well. Pneumatic loads represent the gas flow rates that must be met at a pressure of 25 psig by pneumatic systems when the component is activated.

Component	Count	Activations Per Day	Pneumatic Load [scfh]
Chemical Pump	1	2690	38
Level Controller	1	Continuous	6
Valve Actuator	1	265	678

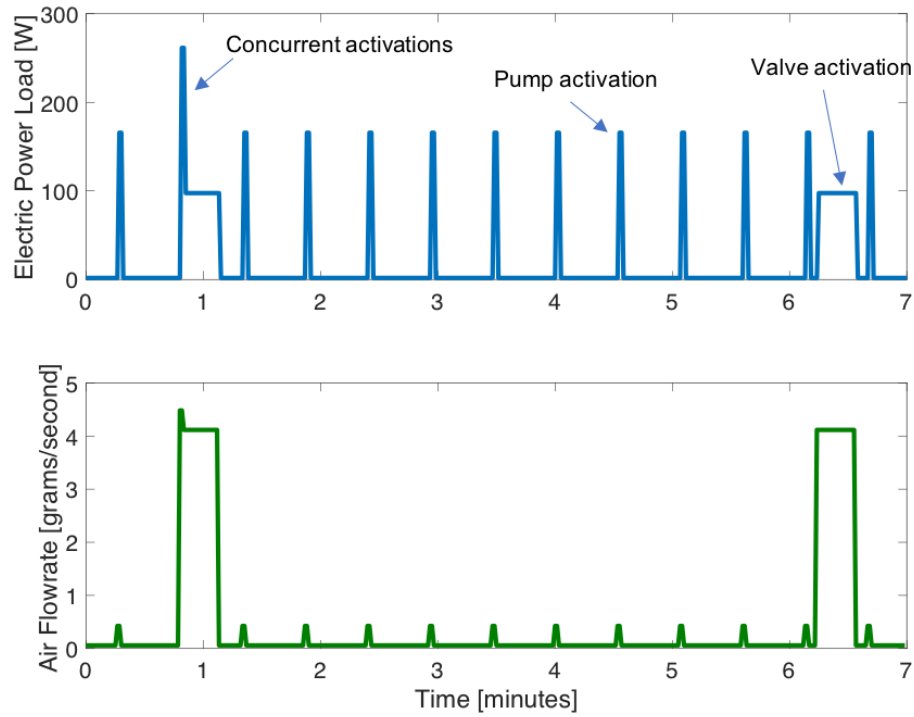


Figure 4.4: Seven minute samples of the electric power and compressed air flowrate loads required by the electric and electro-pneumatic well site control systems respectively. These well site power load profiles are used throughout the analyses discussed in this study. Power loads fluctuate at the intervals shown here throughout a simulated day, but the profile remains consistent day to day. The electric system requires a peak power demand of 262 W and a daily energy load of 430 Wh.

Table 4.2: Summary of key costing analysis parameters and variables. The values of parameters consistent throughout the analysis are shown in the third column, otherwise only units are indicated.

Symbol	Definition	Value [Units]
F^t	System failure at time step t	[binary]
R	System reliability	[%]
$E_{load,e}^t$	Electric energy load of well site equipment at time step t	[J]
$E_{gen,e}^t$	Electric energy generated by system	[J]
$E_{store,e}^t$	Energy stored by system as electricity in batteries	[J]
K_{PV}	Photovoltaic (PV) power generation capacity	[W]
CF_{PV}^t	PV capacity factor	[%]
η_c	Charging efficiency of electric batteries	90%
Δt	Time step interval	s
P_e^t	Electric power load of well site equipment	[W]
d_{lim}	Discharge limit of electric batteries	30%
K_B	Electric battery capacity	[Wh]
$\bar{C}_E$	Cost of avoided methane emissions for electric system implemented at new well site	[\$/tonCH ₄]
C_B	Lead-acids battery capital cost	[\$]
$C_{cont,e}$	Capital cost for electric controller, valve actuator, chemical pump, and control panel	\$16,800
C_{OM}	Operation and maintenance costs for all system components	[\$]
$C_{F,E}^t$	Cost of failure for electric system	[\$]
c_{HH}	Natural gas price	\$2.69/MMBtu
$\dot{V}_{well}$	Well site natural gas production	1 MMScf/day
C_{base}	Cost of baseline pneumatic controller, valve actuator, and chemical pump	\$4,600
M_{CH_4}	Mass of methane emitted by baseline pneumatic system operated with well gas	4.66 ton/year
$E_{gen,p}^t$	Energetic content of air supplied by compressor at time t	[J]
$E_{store,p}^t$	Energetic content of air stored in compressed air tank	[J]
$E_{load,e}^t$	Energetic content of air required by pneumatic equipment	[J]
$\dot{m}_{supply}^t$	Mass flowrate of air supplied by compressor	[kg/s]
h_{supply}	Specific enthalpy of air supplied by compressor	291 kJ/kg
$\dot{m}_{load}^t$	Mass flowrate of air required by pneumatic equipment	[kg/s]
h_{store}^t	Specific enthalpy of air exiting tanks	[kJ/kg]
p_{min}	Minimum gas pressure required by pneumatic equipment	25 psig
p_{store}^t	Pressure of air stored in tank	[psi]
p_{max}	Maximum pressure of air stored in tank	200 psig

V_{tank}	Volume of compressed air tank	[gal]
$\bar{C}_{EP}$	Cost of avoided methane emissions for electro-pneumatic system implemented at new well site	[\$/tonCH ₄]
C_{AC}	Capital cost of air compressor and air dryer	\$12,000
C_{ST}	Capital cost of compressed air storage tank	[\$]
$C_{cont,p}$	Capital cost for pneumatic controller, valve actuator, and chemical pump operated with compressed air	\$6,100
m_P^t	Mass of methane emitted by the electro-pneumatic system	[kg]
$\bar{C}_{E,ret}$	Cost of avoided methane emissions for electric system implemented as a retrofit	[\$/tonCH ₄]
$\bar{C}_{EP,ret}$	Cost of avoided methane emissions for electro-pneumatic system implemented as a retrofit	[\$/tonCH ₄]
C_{shut}	Loss of natural gas revenue resulting from well shut in	\$2,770/day

4.2 Results and Discussion

4.2.1 Solar Photovoltaic Permian Basin

Solar photovoltaic arrays offer a readily available option for powering remote well sites. They are scalable, easily-transportable, cost-effective and are already utilized to power equipment such as chemical pumps. Furthermore, they do not produce on-site GHG emissions. The bulk of the assessment of variable well site power resources in this chapter has, therefore, been applied to determine the reliability and cost of using solar PV with storage to power well sites. However, the same methods may be used to assess other transient energy sources such as wind. In this case study, a well site near Midland, Texas is examined as a representative location in the Permian Basin. The well site configuration and energy demands of the site are discussed in the Well Site Pneumatic System Parameters section above. Local transient solar availability and capacity factors were generated with typical meteorological year (TMY) data using the System Advisory Model (SAM) developed by the National Renewable Energy Laboratory [71].

4.2.1.1 Electric Configuration

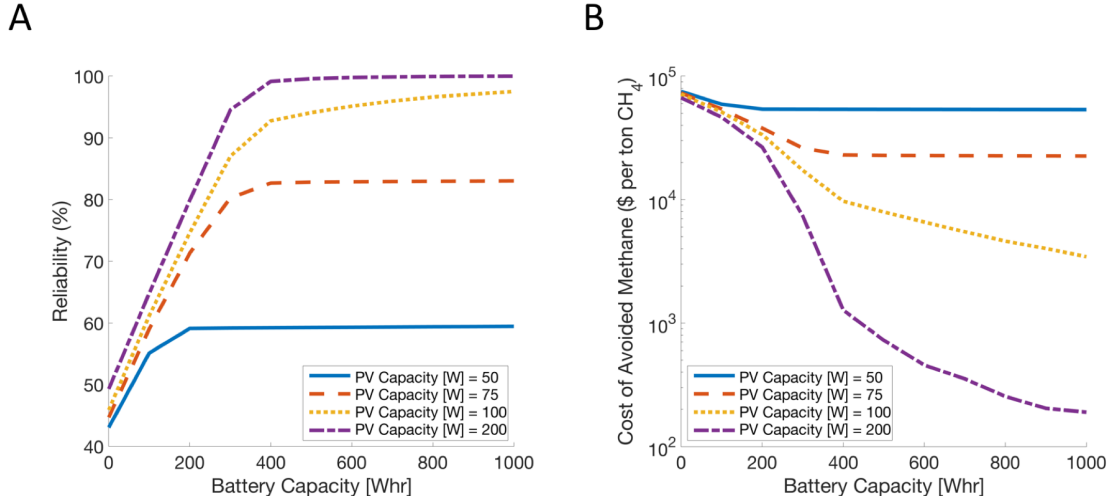


Figure 4.5: System reliability (A) and cost of avoided methane emissions (B) calculated as a function of battery capacity and PV power generation capacity for an electric well site equipment configuration located in the Permian Basin. The appearance of these plots is not smooth since calculations were made with discrete levels of installed battery capacity. These results indicate that even as battery capacity increases, reliability in excess of 98% cannot be achieved without at least 200W of PV capacity.

The results of our simulations of the electric configuration shown in Figure 6 indicate that system reliability and total cost are highly sensitive to installed PV and battery capacity. Reliability improves with increasing battery capacity but will be limited if PV power generation is insufficient. With a PV capacity of 200 W (PV200), the system can achieve a reliability of 99.6% by utilizing 500 Wh of battery capacity. Avoided methane cost is minimized for PV200 with a one kWh battery capacity, which ensures 100% reliability under TMY conditions. One kWh of storage is roughly double the daily energy load of the electric well site control system considered herein. One kWh of storage is also the approximate capacity of a conventional automotive lead-acid battery. The present value of total system costs is \$19,700 under this con-

figuration, while the cost of avoided methane emissions is \$190 per ton of methane. The avoided methane cost is significantly higher for configurations with lower storage capacity as a result of lower reliability. System failures due to insufficient generation and storage are extremely costly when there is no back up system.

4.2.1.2 Electro-Pneumatic Configuration

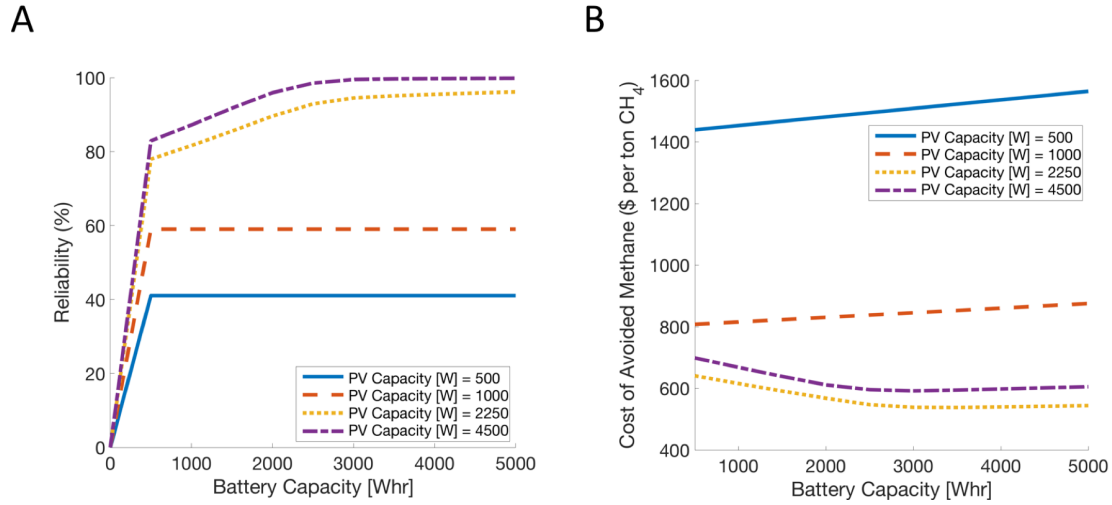


Figure 4.6: System reliability (A) and cost of avoided methane emissions (B) calculated as a function of battery capacity and PV power generation capacity for an electro-pneumatic well site configuration equipped with a 250 gallon compressed air tank located in the Permian Basin. The appearance of these plots is not smooth since calculations were made with discrete levels of installed battery capacity. These figures indicate that reliability will maximize at lower battery capacities than those needed by the electric system since compressed air storage offsets the need for battery storage. The higher power demands of the electro-pneumatic system require larger PV capacities than for the electric configuration.

There are two modes by which the compressed air system can operate to utilize variable solar power generation. The first mode considered here is to utilize compressed air as the primary form of energy storage. Under this mode, the compressor is utilized whenever there is sufficient power supplied from either the PV

system or from the battery. The compressor is turned off when there is insufficient power or when the pressure in the tank exceeds a safe operational pressure, assumed here to be 200 psi. This mode will be referred to here as maximum pressure electro-pneumatic operation (EP-Max). The variation in reliability and the avoided methane cost of this mode under varying PV and battery capacity is shown in Figure 4.6. In comparison to the electric configuration, the EP-Max system requires 2 kW of PV capacity to achieve a reliability above 95%. The electro-pneumatic configuration has greater energy demands than the electric system since energy is lost in the conversion of electricity to compressed air and the utilization of compressed air by pneumatic components. Therefore, a larger PV array is required to generate sufficient electrical energy given the same solar resource. The cost of avoided methane emissions for the EP-Max system is minimized at a PV system reliability of 95% by utilizing 2250W of PV capacity and 4 kWh of battery capacity. The optimal PV capacity under the EP-Max system is higher than that of the electric system. However, the optimal battery capacity is similar due to the supplementary energy storage in the form of compressed air. Furthermore, cost can be minimized at a lower reliability since the whole system does not fail when there is insufficient energy available, resulting in lower failure costs. The minimum cost of avoided methane for the EP-Max system is \$539/tonCH₄, which is significantly higher than the electrical system minimum of \$190/tonCH₄. The present value of total system costs for minimum methane cost configuration is \$42,800. Electric controllers and chemical pumps are more expensive to implement than pneumatic equivalents, but the additional equipment required by the compressed air system necessitate greater investments. The EP-Max system incurs both higher O&M and capital costs due to the larger PV and battery requirements, as well as the necessary air compressor package. The 250 gallon compressed air tank utilized in these simulations constitutes 8% of capital costs, whereas electric batter-

ies only contribute to 4% of capital. While utilizing compressed air as the primary energy storage medium can offset the need for electrochemical battery capacity, it is not necessarily the most economical option.

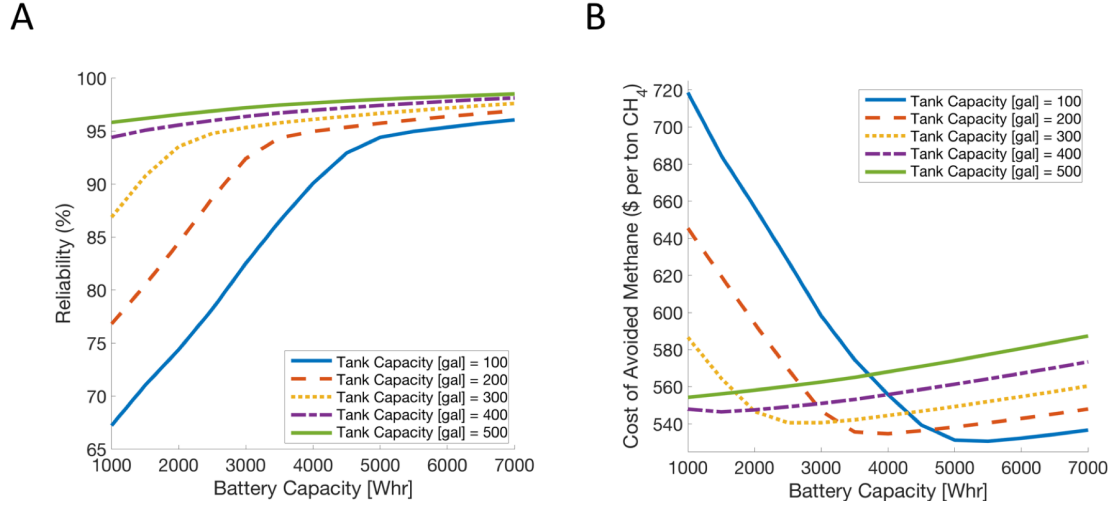


Figure 4.7: System reliability (A) and cost of avoided methane emissions (B) calculated as a function of battery capacity and compressed air tank volume for an electro-pneumatic well site configuration equipped with 2250W of PV capacity located in the Permian Basin. The appearance of these plots is not smooth since calculations were made with discrete levels of installed battery capacity. Increasing the size of the compressed air storage tank further offsets the need for electric battery storage. However, increasing compressed air storage capacity is not necessarily economical.

Under the EP-Max configuration, reliability and cost will depend on compressed air tank volume since it utilizes compressed air as the primary energy storage medium. The sensitivity of the EP-Max system to air tank volume and battery capacity for a system with 2250 W of PV is shown in Figure 4.7. Increasing compressed air storage capacity increases reliability, particularly with battery capacities below 2 kWh. However, Figure 4.7B indicates that offsetting battery capacity with compressed air storage is not always economical. At electrochemical battery capacities above 3 kWh, the cost of avoided methane emissions increases with increasing air

storage volume for tanks larger than 300 gallons. As with the results shown in Figure 4.6, minimum cost of avoided methane emissions is achieved with a reliability of 94%. However, the cost of avoided methane emissions is reduced to \$530/tonCH₄ by utilizing a smaller air tank of 100 gallons but a larger battery capacity of 5.5 kWh.

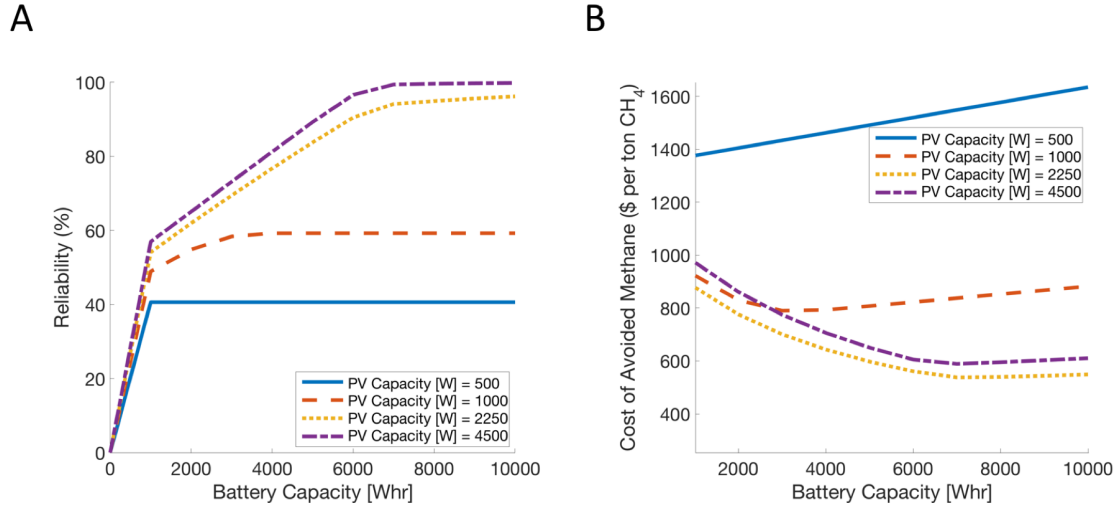


Figure 4.8: System reliability (A) and cost of avoided methane emissions (B) calculated as a function of battery capacity and PV power generation capacity for an electro-pneumatic system located in the Permian Basin operated to maintain minimum pressure with batteries as the primary storage mechanism. The appearance of these plots is not smooth since calculations were made with discrete levels of installed battery capacity. The system is equipped with a small 25 gallon compressed air tank to maintain minimum air pressure. This mode of operation requires larger electric battery capacity but can be more stable and similarly economical to utilizing compressed air as the primary storage medium.

The results shown in Figure 4.8 indicate that while utilizing compressed air as the primary form of energy storage is technically feasible, it is not necessarily economical. A more viable mode of operation under the electro-pneumatic configuration could be to utilize the lead-acid battery as the primary energy storage medium. In this mode, which we will refer to as EP-Min, the compressor would only be operated to maintain a minimum pressure in the compressed air tank, allowing more energy

to remain in the form of electricity stored in the battery bank instead of regularly converting energy to compressed air. Compressed air systems are conventionally operated in this mode. The EP-Min system can therefore operate with a small surge tank and reliability will be independent of air tank volume. Figure 4.8 illustrates how the reliability and lifetime cost of avoided methane emissions of an EP-Min system equipped with a 25 gallon air tank will vary with installed PV and battery capacity. The electrochemical battery capacity required to achieve high system reliability is greater for the EP-Min configuration than for the EP-Max mode while PV capacity demands are similar. The cost of avoided methane emissions is minimized again at 94% reliability with 2250 W of PV capacity. However, this level of reliability requires 7 kWh of electrochemical battery capacity. If system reliability is a greater priority, higher reliability can be achieved under TMY conditions by investing in more PV and battery capacity. Despite the increased utilization of battery storage under the EP-Min configuration, the minimum cost of methane abatement is \$538/tonCH₄ since the system can operate with a significantly smaller air tank. The present value of total system costs for this configuration is \$41,900. The potential costs are similar for both the EP-Min and EP-Max configurations. The relative cost advantage of the EP-Min system with respect to EP-Max system is sensitive to the lifetime cost of the electrochemical batteries. If the lead-acid batteries must be replaced more often than every five years due to frequent charge cycling, extreme weather conditions or theft, then offsetting electric battery capacity with a larger air storage tank under the EP-Max configuration might be more economical. The cost of electrochemical batteries would increase further if embedded environmental or social externalities are accounted for, particularly cobalt-containing lithium-ion batteries [72]. However, operators would likely prefer EP-Min systems as they are operationally similar to conventional compressed air systems. It should also be noted that the EP-Min configuration would

be more thermodynamically efficient as operating at lower pressures reduces energy losses due to heat transfer and pressure reduction. Electric batteries are a more stable energy storage medium, particularly over extended periods of time.

These comparisons yield insights on the utilization of compressed air storage versus electrochemical battery storage. For the systems and power loads examined here, battery-based energy storage is likely the more practical and cost-effective option. While battery storage is often seen as a costly hurdle to integration of variable power generation at the utility scale, electrochemical batteries are a relatively affordable option for reducing the cost of avoided methane emissions. Electrochemical batteries are recommended as the primary form of energy storage for the electro-pneumatic configuration due to their energy density, modularity, availability, and relative affordability.

4.2.1.3 Retrofit Scenario Costing

The analysis above indicates that a solar-powered electric well site system would be more cost effective than a compressed air pneumatic system when implemented at a new well site. However, these systems can also be used to retrofit an existing well site to reduce future methane emissions. In a retrofit scenario, the electric system might be costlier to implement because a new set of electric components would need to be installed and maintained, whereas the compressed air system could utilize existing pneumatic controllers and chemical pumps. Furthermore, the well must be shut down when electric systems are installed and replaced. To assess the difference in avoided methane costs for retrofit systems, the costing equations for the electric and electro-pneumatic systems were modified as shown in Equations 4.14 and 4.15. Here, the evaluation period is reduced to 10 years and the cost of the baseline pneumatic system is not subtracted from the total system costs. The loss of revenue

resulting from shutting the well when installing the electric system is factored in as the parameter C_{shut} . Equation 4.16 describes how C_{shut} is calculated as the product of natural gas price (c_{HH}) and the volume of natural gas produced by the well during a time step ($\dot{V}_{well}$). The shutdown period (T_{shut}) is assumed to be one day, resulting in a loss of revenue equivalent to \$2,770.

$$\bar{C}_{E,ret} = \frac{PVal(C_{PV} + C_B + C_{cont,e} + C_{OM} + \sum_{t=1}^T C_{F,E}^t)}{M_{CH_4}} \quad (4.14)$$

$$\bar{C}_{EP,ret} = \frac{PVal(C_{PV} + C_B + C_{OM} + C_{AC} + C_{ST})}{M_{CH_4} - \sum_{t=1}^T m_P^t} \quad (4.15)$$

$$C_{shut} = T_{shut} \times c_{HH} \times \dot{V}_{well} \quad (4.16)$$

Revaluating the solar-powered systems discussed above as retrofits increases the total system cost of the 100% reliable electric system from \$19,700 to \$21,900 at a well site located in the Permian Basin. In contrast, the total system cost of the EP-Max system with a reliability of 94% decreases from \$41,900 to \$32,100. The avoided methane costs increase to \$436/tonCH₄ and \$658/tonCH₄ and for the electric and EP-Min systems respectively. It should be noted that, in some studies, the quantity of avoided emissions is discounted in addition to expenses when evaluating the cost methods to reduce GHG emissions [52]. If a 3% discount rate was applied to avoided methane emissions, the minimized avoided methane costs would increase by 25% and 18% for new and retrofitted well sites respectively. Even so, the costs of the systems examined here would remain under \$800/tonCH₄. Methane abatement costs increase for retrofits as the shorter evaluation period results in fewer methane emissions avoided over the systems lifetime. Even so, the electric system is still the

lower cost option of the two configurations. However, the difference in cost between the two configurations decreases from \$348/tonCH₄ and to \$223/tonCH₄ and when comparing a new site and a retrofit because a retrofitted electro-pneumatic system does not incur capital costs for controllers and chemical pumps. The cost advantage of the electric system is highly sensitive to the time required to shut-in the well during installation. Here the shut-in period is set to one day. However, shutting the well for just five days would increase the avoided methane cost of the electric system to \$673/tonCH₄ and, thus switching the cost advantage to the electro-pneumatic system.

4.2.1.4 Worst-case Solar Resource Simulation

The results above discuss the PV generation and energy storage requirements needed to operate an electrified well site control system reliably and economically when considering a year with typical (TMY) solar insolation conditions. However, these systems must be robust enough to operate under periods of anomalously low solar availability to prevent costly production downtime. To account for atypical solar resources, SAM was used to generate new datasets of worst-case time-varying solar capacity factors based on historical data to use as inputs to the simulations discussed above. Seventeen years of historical solar insolation data for the location in Midland, TX were analyzed on a month-by-month basis. Every worst-case month over the seventeen-year period was then combined to create a hypothetical worst-case meteorological year of solar availability, which we is referred to here as WMY-1M conditions. A second worst-case year was created using five-day increments, which is referred to here as WMY-5D conditions. The WMY-5D year is the scenario with the poorest solar availability, and results in a one-year average capacity factor of 14%. For comparison, the WMY-1M and TMY conditions result in average capacity factors of 18% and 20% respectively.

Table 4.3: Summary of reliability and total system cost for electric and electro-pneumatic well site control systems located in the Permian Basin powered by solar photovoltaic generation under varying one-year solar resource conditions. The parameters shown for TMY conditions are those which minimize the cost of reliability. The lower solar availability under the WMY scenarios result in lower reliabilities. However, systems can be made more robust by utilizing additional PV and/or battery capacity.

Configuration	Resource Scenario	PV Capacity [W]	Battery Capacity [kWh]	Reliability [%]	Total System Present Cost [\$]
Electric	WMY-1M	200	1	99	19700
	WMY-5D	200	1	97	19700
	TMY	200	1	100	19700
	WMY-1M	250	2	100	20400
	WMY-5D	250	2	100	20400
Electro-Pneumatic (EP-Min)	WMY-1M	2250	7	87	41900
	WMY-5D	2250	7	76	41900
	TMY	2250	7	94	41900
	WMY-1M	3500	8	94	45900
	WMY-5D	4000	13	94	50000

The electric system and the electro-pneumatic system under the EP-Min operation mode were simulated for a new well site using the WMY solar resource inputs. The results shown in Table 4.3 illustrate how the optimal PV generation and electric battery storage capacities selected under TMY conditions will have lower reliabilities and higher total system costs under WMY conditions due to decreased availability and consistency of the solar resource. The reliability of the EP-Min system optimized to TMY conditions is 19% lower under the WMY-5D scenario. The drop in reliability is smaller for the electric system due to its lower energy demands. Utilizing an additional kilowatt-hour of battery capacity and 50W of PV capacity ensures 100% reliability and only increases total system cost by 4% for the electric system under both WMY conditions. This result highlights how the lower power demand of the electric system reduces its sensitivity to fluctuations in solar resources. Increases in both PV generation and battery storage are required to minimize system costs for the electro-pneumatic system and maintain system reliability under the WMY re-

source scenarios. The cost of reliability for the EP-Min configuration is minimized at a reliability of 94% under TMY conditions. However, the added PV and battery capacity needed to meet 94% reliability under the WMY-1M and WMY-5D scenarios results in total system costs of \$45,900 and \$50,000 respectively. The additional PV and battery capacities needed to maintain the same level of reliability for the EP-Min system are much greater than those required by the electric system. While the worst-case scenarios examined here, particularly the WMY-5D condition, are unlikely to realistically occur in the field, these results show that economic levels of reliability can be maintain with investments in additional PV and electric battery capacities.

4.2.2 Solar Photovoltaic Haynesville Formation

The Haynesville Formation located in eastern Texas presents another oil and natural gas production region where solar photovoltaic energy can potentially be used to electrify a well site and replace conventional pneumatic systems. To assess the viability of utilizing solar PV in the Haynesville region, we applied the same analysis for a well site near Midland, TX discussed above for a hypothetical well site located near Nacogdoches, TX. Most of the simulation parameters were kept the same including the control system inventory and power load. However, new time-varying capacity factors were simulated using SAM for a PV system located at the East Texas site. The simulated Nacogdoches PV system resulted in a one-year average capacity factor of 16% in comparison to the 20% capacity factor of the Midland system. Despite its location at approximately the same latitude as Midland, local weather conditions at the Nacogdoches site result in decreased solar availability.

4.2.2.1 Electric Configuration

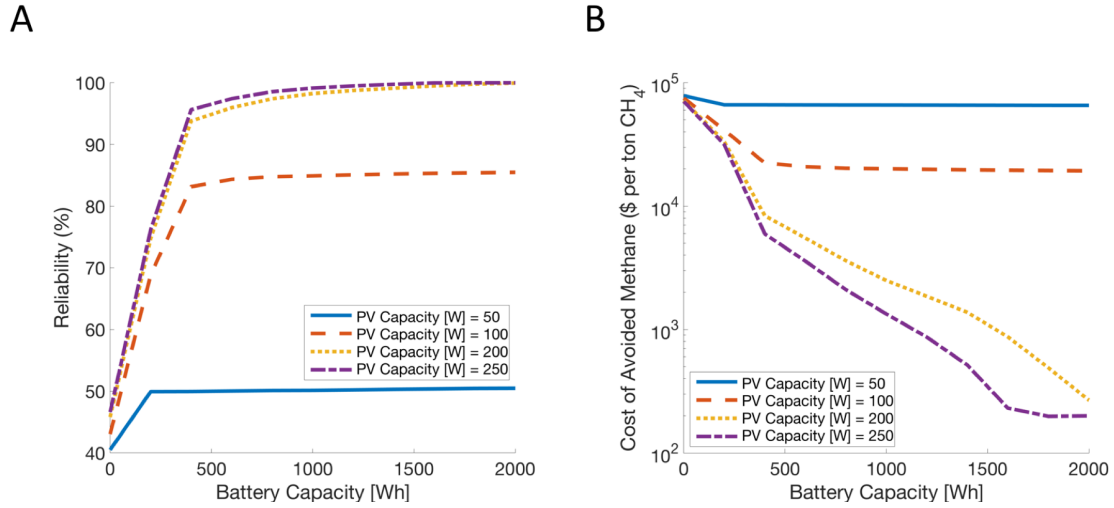


Figure 4.9: System reliability (A) and cost of avoided methane emissions (B) calculated as a function of battery capacity and PV power generation capacity for an electric well site equipment configuration located in the Haynesville. The appearance of these plots is not smooth since calculations were made with discrete levels of installed battery capacity. In comparison to the Midland site, the reliability of the simulated systems with the same PV and battery capacities are generally lower due to the lower solar availability near Nacogdoches. Here, cost is minimized with a 250W system, which enables 100% reliability under TMY conditions

The results of simulations of the electric configuration shown in Figure 4.9 indicate that a control system located near Nacogdoches will require greater PV and battery capacities than the Midland system to achieve the same level of reliability due to the lower local solar availability. With a PV capacity of 200 W, the Haynesville system can only achieve a reliability of 95% by utilizing 500 Wh of battery capacity. Avoided methane cost is minimized for a system with a 250W PV array and a two kWh battery capacity, which ensures 100% reliability under TMY conditions. Two kWh of storage is roughly double the battery capacity required by the electric well site control system considered in Midland. Despite the increased PV and battery

capacities required at the Haynesville site, the systems cost is minimized to just \$198 per ton of avoided methane emissions. While the East Texas system could achieve a very high degree of reliability with the optimal configuration of the West Texas system (98%), less than 100% reliability is very costly when there is no back up system. It is costlier to ensure higher reliability at the Nacogdoches site, but 100% reliability can be achieved by increasing battery capacity to 2 kWh while only increasing total system cost from \$19,700 to \$20,200. Therefore, additional PV power generation and battery capacities are required to compensate for lower solar availability. The resulting increase in costs are fairly minimal when considering the cost of the total system over the 15-year evaluation period of the site.

4.2.2.2 Electro-Pneumatic Configuration

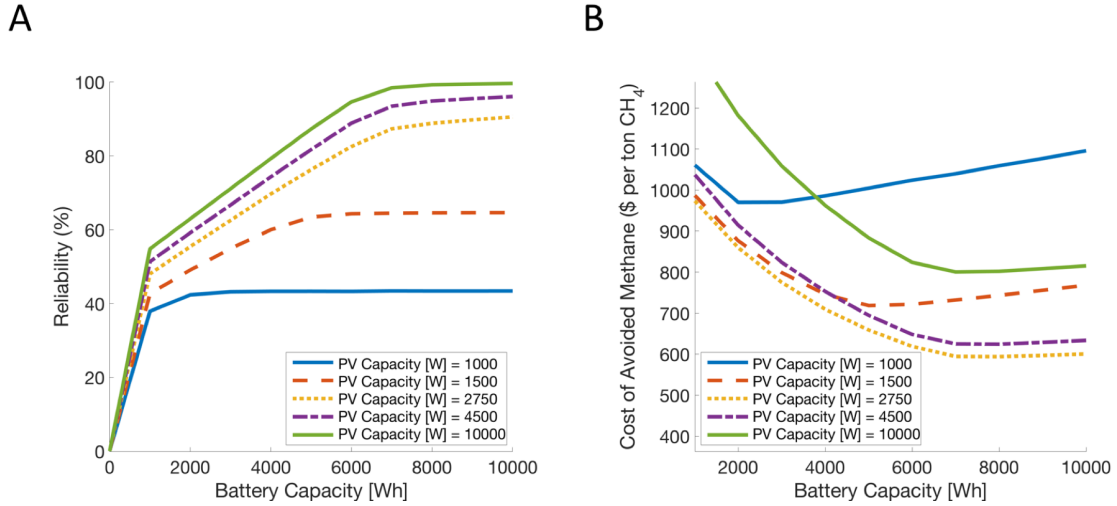


Figure 4.10: System reliability (A) and cost of avoided methane emissions (B) calculated as a function of battery capacity and PV power generation capacity for an electro-pneumatic system located in the Haynesville operated to maintain minimum pressure with batteries as the primary storage mechanism. The appearance of these plots is not smooth since calculations were made with discrete levels of installed battery capacity. The system is equipped with a small 25 gallon compressed air tank to maintain minimum air pressure. The system at this location requires approximately 20% greater PV power generation and battery capacities than the Midland system to minimize the cost of avoided methane.

A solar-powered electro-pneumatic control system under the EPMin configuration was simulated for a well site located in the Haynesville region with varying PV power generation and electric battery capacities. The results shown in Figure 4.10 again indicate that additional PV generation and electric battery capacities are required to maintain system reliability and minimize the cost of avoided methane emissions in comparison to a similar site located in the Permian Basin. For a site located near Nacogdoches, the avoided cost of methane is minimized at \$594/tonCH₄ for a system with approximately 2750W of PV generation and 8 kWh of battery storage, resulting in a total system present cost of \$44,100. The EPMin system located in

East Texas requires an even greater in PV capacity due to the higher power demands of the EPMin configuration relative to the fully electric equivalent to compensate for decreased solar resource. Avoided methane costs are minimized at a reliability of 89% for the Haynesville site, whereas costs are minimized at 94% reliability at Midland. Unlike the electric configuration, the electro-pneumatic configuration can be coupled with the existing well gas system. Having a back-up system allows for greater flexibility in how reliably the PV power generation must meet power loads. System reliability could be improved to 94% by increasing PV capacity to 4500W, thus increasing total cost to \$48,300. However, the added system cost would not compensate for the reduction in emitted methane, resulting in an avoided methane cost of \$624/tonCH₄.

4.2.2.3 Worst-case Solar Resource Simulation

Table 4.4: Summary of total system present cost and reliability for electric and electro-pneumatic well site control systems located in the Haynesville Formation powered by solar photovoltaic generation under varying one-year solar resource conditions. The parameters shown for TMY conditions are those which minimize the cost of reliability. The lower solar availability under the WMY scenarios result in lower reliabilities. However, systems can be made more robust by utilizing additional PV and/or battery capacity.

Configuration	Resource Scenario	PV Capacity [W]	Battery Capacity [kWh]	Reliability [%]	Total System Present Cost [\$]
Electric	WMY-1M	250	2	99	20400
	WMY-5D	250	2	94	20400
	TMY	250	2	100	20400
	WMY-1M	325	2	100	20500
	WMY-5D	400	3	100	21300
Electro-Pneumatic (EP-Min)	WMY-1M	2750	8	81	44100
	WMY-5D	2750	8	69	44100
	TMY	2750	8	89	44100
	WMY-1M	4000	9	89	47600
	WMY-5D	4500	18	89	53900

The electric system and the electro-pneumatic system under the EP-Min operation mode were simulated for a new well site using WMY solar resource inputs generated for a site located in the Haynesville. The WMY-5D scenario simulated near Nacogdoches, TX results in a one-year average capacity factor of 10%, while the WMY-1M and TMY conditions result in average capacity factors of 14% and 16% respectively. The results shown in Table 4.4 illustrate lower reliabilities and higher total system costs that are similar to the trends seen in the Permian Basin when PV generation and electric battery storage capacities selected under TMY conditions are simulated with WMY conditions. The reliability of the EP-Min system with minimized methane abatement cost under TMY conditions is 20% lower under the WMY-5D scenario while the electric system experiences a reduction in reliability of 6%. The drop in reliability from TMY to WMY conditions is generally greater for the Haynesville location than for the Permian site. However, the additional battery capacities needed to maintain optimal TMY reliability of the electric system under WMY conditions are consistent between the two locations. At both Midland and Nacogdoches, utilizing just one additional kilowatt-hour of battery capacity ensures reliability at TMY conditions for the electric system under both WMY scenarios. The the Nacogdoches system requires an additional 150W of PV capacity to compensate for the reduced solar availability of the WMY-5D scenario, but these investments represents just a 4% increase in total system cost relative to the TMY case. In comparison to the fully electric configuration, the additional investments required to maintain reliability of the electro-pneumatic system are greater under both WMY scenarios due to its higher power demands. The additional PV and battery capacities are even greater than those required for the same scenarios at the Midland site. At both sites, however, maintaining the reliability of the TMY EP-Min configuration under the WMY-1M and WMY-5D scenarios requires 8% and 22% increases in total

system cost respectively. These results indicate that, despite the typically lower solar availability in the Haynesville region, the relative increase in cost of oversizing the system to maintain an economic degree of reliability is consistent between the two locations in Texas.

4.2.3 Solar Photovoltaic Kaybob-Duvernay Region

The final oil and natural gas production region we have applied our analysis to is the Kaybob-Duvernay region located in west of Edmonton, Canada. Solar PV energy is not commonly utilized for utility-scale power generation in such northern regions of Canada due to the relatively low solar resource. However, solar PV is still a relatively low-cost power generation option that can be deployed at electrified well sites in remote regions of western Alberta. To assess the viability of utilizing solar PV in the Kaybob region, we applied the same analysis for the hypothetical well sites located in Texas discussed above for a new well site located just west of Edmonton. All simulation parameters were kept the same including the control system inventory and power load. However, new time-varying capacity factors were simulated using SAM for a PV system located at the Canadian site. The simulated Kaybob PV system resulted in a one-year average capacity factor of 11%, nearly half the capacity factor of the Midland system. The lower capacity factor is due to the lower solar resource at the significantly more northern location as well as losses due to snow cover of PV panels. Snow cover losses were estimated to reduce power generation by 55% during the months of November through March using relations developed by NREL and historical snow depth data for Edmonton [73, 74].

4.2.3.1 Electric Configuration

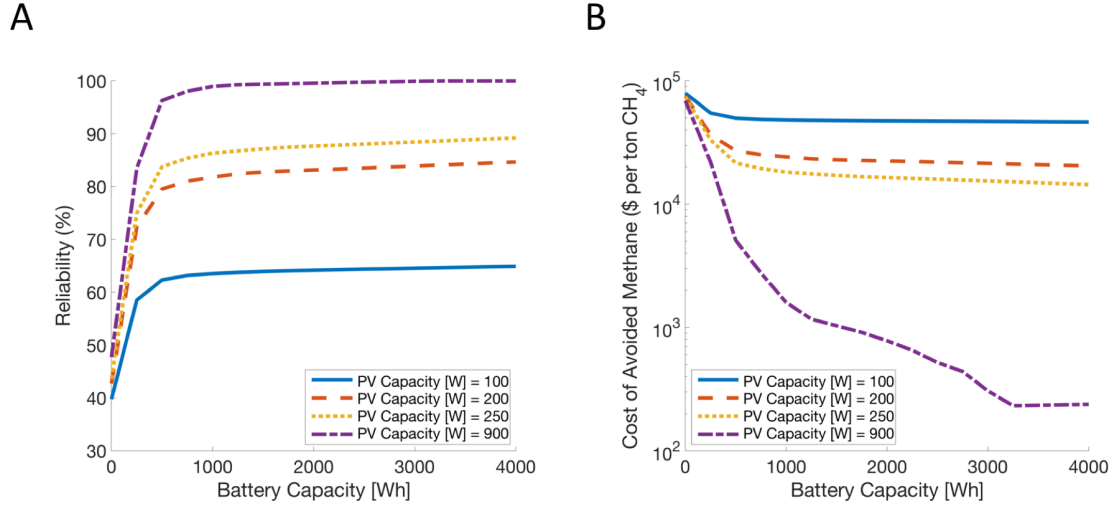


Figure 4.11: System reliability (A) and cost of avoided methane emissions (B) calculated as a function of battery capacity and PV power generation capacity for an electric well site equipment configuration located in the Kaybob region of Alberta. The appearance of these plots is not smooth since calculations were made with discrete levels of installed battery capacity. In comparison to the Texas sites, the reliability of the simulated systems with the same PV and battery capacities are considerably lower due to the lower solar availability near Edmonton. Here, cost is minimized with a 900W system, which enables 100% reliability under TMY conditions

The results of our simulations of the electric configuration shown in Figure 4.11 indicate that a control system located near Edmonton, Canada will require significantly greater PV and battery capacities than both Texas systems to achieve the same level of reliability due to the lower local solar availability. With a PV capacity of 200 W, the Kaybob system can only achieve a reliability of 80% by utilizing 500 Wh of battery capacity. Avoided methane cost is minimized for a system with a 900W PV array and a 3 kWh battery capacity, which ensures 100% reliability under TMY conditions. The PV and battery capacities required here are more than three times those needed to maintain 100% reliability at TMY conditions in the Permian

Basin. This result highlights the importance of simulating a full year of operation and not only seasonal or annual averages. The system must consider days with especially low solar availability to ensure full reliability over the year. Due to the extreme seasonality of solar availability in northern climates, the lowest one-day capacity factor for the Kaybob site is less than 0.5% under TMY conditions. In contrast, one-day capacity factor in the Permian region only falls to 5%. The larger PV system of the optimal Kaybob site results in a total system cost of \$22,500 and a minimized avoided methane cost of \$232/tonCH₄. While the electric system would be up to 20% more expensive to implement, the avoided cost of methane for the electric system located in Alberta is still less than half the cost of the electro-pneumatic systems that could be implemented at new well sites in Texas.

4.2.3.2 Electro Pneumatic Configuration

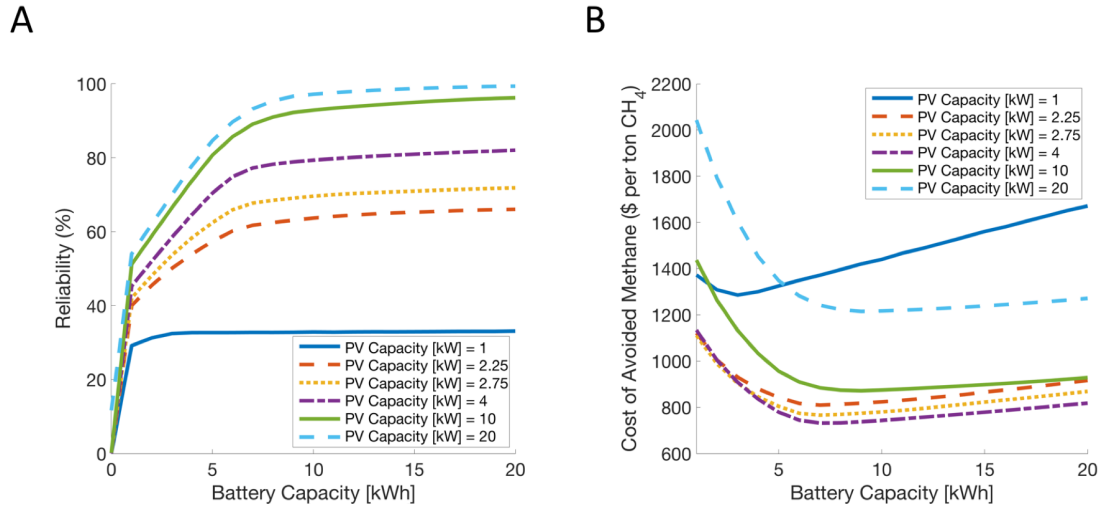


Figure 4.12: System reliability (A) and cost of avoided methane emissions (B) calculated as a function of battery capacity and PV power generation capacity for an electro-pneumatic system located in the Kaybob region of Alberta, Canada operated to maintain minimum pressure with batteries as the primary storage mechanism. The appearance of these plots is not smooth since calculations were made with discrete levels of installed battery capacity. The system is equipped with a small 25 gallon compressed air tank to maintain minimum air pressure. The system at this location requires at least 45% greater PV power generation capacity than either of the two systems located in Texas to minimize the cost of avoided methane.

A solar-powered electro-pneumatic control system under the EP-Min configuration was simulated for a well site located in the Kaybob region with varying PV power generation and electric battery capacities. The results shown in Figure 4.12 again indicate that additional PV generation and electric battery capacities are required to maintain system reliability and minimize the cost of avoided methane emissions in comparison to similar sites located in the Permian Basin and Haynesville Formation. For a site located near Edmonton, the avoided cost of methane is minimized at \$732/tonCH₄ with approximately 4000 W of PV generation and 7 kWh of battery storage. The battery capacity of the minimum-cost system is lower than

that of the equivalent system analyzed in the Haynesville region. However, avoided methane costs are minimized at a reliability of just 77% for the Kaybob site. As the availability of solar resources degrades, it becomes less economical to invest in greater PV and battery capacities to maintain operation of the electric compressor. However, the effectiveness of the system comes into question if only approximately 80% of methane emissions are being avoided. Similar reductions in emissions might be achieved more cost-effectively simply by replacing high-bleed controllers with no-bleed controllers and performing preventative maintenance more regularly [28]. System reliability could be improved to 94% by increasing PV capacity to 10kW and battery capacity to 13 kWh. However, the added system cost would not compensate for the reduction in emitted methane, resulting in an avoided methane cost of \$888/tonCH₄. Furthermore, spacial constraints might arise at well pads with a high density of well-heads that would preclude the installation of such large PV arrays. Achieving even higher reliabilities becomes highly cost-intensive. A PV system with 20 kW of power generation capacity and 20 kWh of storage still cannot achieve 100% reliability under TMY conditions in the Kaybob region.

4.2.3.3 Worst-case Solar Resource Simulation

Table 4.5: Summary of total system present cost and reliability for electric and electro-pneumatic well site control systems located in the Kaybob-Duvernay region powered by solar photovoltaic generation under varying one-year solar resource conditions. The parameters shown for TMY conditions are those which minimize the cost of methane abatement. The lower solar availability under the WMY scenarios result in lower reliabilities. However, systems can be made more robust by utilizing additional PV and/or battery capacity.

Configuration	Resource Scenario	PV Capacity [W]	Battery Capacity [kWh]	Reliability [%]	Total System Present Cost [\$]
Electric	WMY-1M	900	3	99	36800
	WMY-5D	900	3	93	36800
	TMY	900	3	100	36800
	WMY-1M	1250	4	100	38200
	WMY-5D	1650	5	100	39800
Electro-Pneumatic (EP-Min)	WMY-1M	4000	7	68	46500
	WMY-5D	4000	7	55	46500
	TMY	4000	7	77	46500
	WMY-1M	4750	15	77	52800
	WMY-5D	7750	20	77	62800

The electric system and the electro-pneumatic system under the EP-Min operation mode were simulated for a new well site using WMY solar resource inputs generated for a site located in the Kaybob-Duvernay region. The WMY-5D scenario simulated near Edmonton, Canada results in a one-year average capacity factor of 6%, while the WMY-1M and TMY conditions result in average capacity factors of 9% and 11% respectively. The results shown in Table 4.5 illustrate how significant investments in additional PV power generation and electric battery capacities beyond those required by the TMY scenario must be made to ensure a high level of reliability under worst case conditions. The reliability of the EP-Min system selected at TMY conditions is 22% lower under the WMY-5D scenario while the electric system experiences a reduction in reliability of 7%. The reliability is lower and the total system cost is higher under all scenarios and configurations for the Kaybob location than for the Texas sites. However, the additional battery capacities beyond those required by

the TMY scenario needed to maintain reliability for the electric configuration under WMY-1M conditions are consistent between all locations. Utilizing just one additional kilowatt-hour of battery capacity ensures consistent reliability between TMY and WMY-1M scenarios. However, the Kaybob system requires an additional 350 W of PV power generation capacity as it becomes increasingly difficult to compensate for the reduced solar availability of the WMY-1M scenario.

The additional investments required to maintain the reliability of the electro-pneumatic system under the WMY scenarios are even more onerous than those required by the electric system. Maintaining just 77% reliability under the WMY-5D scenario requires a 35% increase in system cost with respect to the TMY scenario. In comparison, 90% reliability can be maintained at the Haynesville site with just a 20% cost increase for the same scenarios. The EP-Min system might be an appealing option for electrifying a well site located near Edmonton if the system can be backed up with conventional well gas pressure to operation of the well site during periods of extremely low solar availability that occur in the Kaybob region. However, the effectiveness of the solar-powered system comes into question if it only supplies enough power to operate the system 77% of the time, as is the case for the EP-Min system under all scenarios. The fully electric configuration can be risky to implement without a back-up system in regions with such inconsistent solar availability. However, these results indicate that it is more economical to oversize the PV and battery storage system of the electric configuration to account for extreme cases of low solar availability than to utilize the EP-Min configuration. An oversized system could be made more economical if the excess power generated during the summer month could be utilized for auxiliary power loads or sold to local consumers.

4.2.4 Solar Photovoltaic Comparison of Regions

Table 4.6: Summary of total system present costs required to maintain varying degrees of reliability for electric and electro-pneumatic control systems implemented at new well sites located in all three regions powered by solar photovoltaic generation under TMY solar resource conditions. In addition to the cost of the electric air compression system, the greater PV and battery capacities required by the electro-pneumatic system make it at least twice as costly to implement at all locations. Costs are significantly higher for the Kaybob site than for both sites in Texas due to its considerably poorer solar resources.

Config.	Reliab.	Permian			Haynesville			Kaybob		
		PV Cap. [W]	Batt. Cap. [kWh]	Total Cost [\$]	PV Cap. [W]	Batt. Cap. [kWh]	Total Cost [\$]	PV Cap. [W]	Batt. Cap. [kWh]	Total Cost [\$]
Electric	100%	200	1	19700	200	2	20200	900	3	22500
	98%	100	1	19400	200	1	19700	550	2	21100
	95%	100	0.6	19200	100	1	19600	400	1.5	20400
	90%	100	0.4	19100	100	0.4	19100	300	1.5	20200
Electro-Pneumatic (EP-Min)	98%	3000	9	45300	5000	13	52300	13000	20	75300
	95%	2250	8	42900	4000	10	48200	9000	18	64600
	90%	2250	6	41200	3000	8	44700	6750	13	55900
	80%	2000	5	38200	2000	8	42300	4750	7	48300

The simulations of solar-powered well site control systems reveal distinct differences in total system cost between the two control system configurations and between the three regions of interest. The results summarized in Table 4.6 show that it is at least twice as costly to implement the PV-powered electro-pneumatic system at a new well site than it is to implement an equivalent fully electric system at the same degree of reliability in all three regions. Electro-pneumatic systems can require over twenty times the PV power generation capacity needed by the fully-electric equivalent to achieve the same degree of reliability due to their higher power demands. In general, the difference in cost increases at higher degrees of reliability and in regions with lower solar availability. For instance, the EP-Min system is roughly twice as costly as the electric system with 90% reliability at the Permian site but 3.5 times as costly if 98% reliability is required at the Kaybob site. While the cost of the electric

system can be reduced by sizing the PV and battery system to lower reliabilities, the cost of methane abatement is minimized at 100% reliability for all locations. If operators decide to implement a solar-powered electric system at a well site, there is no techno-economic benefit to installing a PV and battery system smaller than one which minimizes the cost of avoided methane emissions. However, for the electro-pneumatic configuration, the increase in costs required to ensure greater than 95% reliability are no longer marginal.

Regional differences in climate results in varying total system costs for solar-powered well sites located in the Permian and Haynesville regions. However, the most significant variation in cost exists between systems located in the Kaybob region and systems located in the two Texas sites. With respect to the Permian site, a fully electric system located in the Haynesville requires one additional kWh of battery storage to achieve 100% reliability, which results in just a \$500 or 2.5% increase in total system cost. An equivalently reliable system located in the Kaybob region requires significantly greater PV generation capacity as well as additional energy storage due to the significantly lower and less consistent solar resource. The larger PV and battery system required by the Kaybob site results in over a \$2,300 or 11% increase in cost relative to both Texas sites. Regional differences in cost are even more significant for the electro-pneumatic system as its higher demands make its reliability and cost more sensitive to variations in solar availability. It is important to note that reliability and required system costs do not scale directly with the annual capacity of PV systems in these regions. The difference in PV capacity factor between the Kaybob and Haynesville regions is similar to the difference in capacity factor between the two Texas regions. However, the marked seasonal difference in solar availability in northern Alberta necessitates significant investment in additional PV and energy storage capacities to ensure reliable supply of power during the winter.

The cost-effectiveness of solar-powered electrified well site control systems as a technique to avoid methane emissions will depend on the monetary cost attached to methane emissions. One useful metric is the US EPA’s social cost of methane. Under the Obama administration, the EPA valued the social cost of methane as \$1,200/tonCH₄ for the year 2020 when considering a 3% discount rate [75]. All minimized methane abatement costs calculated here are well below this value. The solar-powered systems examined here could therefore be considered cost-effective, even systems located in Alberta where significant investments in PV and battery capacity would be needed to overcome low levels of insolation. However, the Trump administration EPA amended the social cost methane to just \$180/tonCH₄ in October of 2017 [76]. In reference to this value, solar-powered well site electrification might not be cost-effective at any of the locations examined in this study. The electric systems analyzed for the locations in Texas would result in methane abatement costs just 5-10% greater than the amended social cost of methane. However, all other minimized methane abatement costs found here are significantly greater, particularly those calculated for the EP-Min systems.

4.2.5 Wind

The same methodology could potentially be used to analyze viability of utilizing wind resources for powering remote well sites for future work. Wind has unique benefits and drawbacks compared to solar. Wind can achieve higher capacity factors, particularly if large turbines are installed that utilize tall towers to access higher average wind speeds. As seen in Figure 2.1. The capacity factor for wind in West and Northwest Texas can exceed 50% for 80 meter hub heights. High capacity factors in West Texas suggests that wind could be a viable alternative energy source to be considered for the Permian Basin. However, when it comes to other regions of the state,

the viability of wind can drop off significantly where in other regions, such as East Texas, the capacity factor is less than 10%. On the other hand, the capacity factor for solar ranges from 15%21%, meaning that viability of solar PV is likely to be more consistent across the state, including the Permian Basin (west Texas) and Haynesville (east Texas). Utility scale wind is also viable in some regions of the Kaybob-Duvernay (Eastern Alberta, Canada) formation [77, 78]. However, most of the higher capacity factor regions exist close to the US-Canadian border and along the eastern edge of the Canadian Rocky Mountain range, away from the specific location considered in this study.

Utilizing wind power for oil and gas operations has drawbacks. Wind, unlike solar PV, does not scale well to smaller sizes. Smaller turbines with kW-scale exist but they have higher costs when levelized per kWh of generated electricity, in part due to their low hub heights and subsequently lower capacity factors. Commercial wind turbines are now regularly deployed with capacities of 2 MW, orders of magnitude more power than is needed for the electricity requirements of the control systems discussed in this report. It is technically feasible that the electricity demands of multiple wells could be supplied from a single turbine. However, it is unlikely to be economical compared to the modular nature of solar PV.

4.2.6 Geothermal

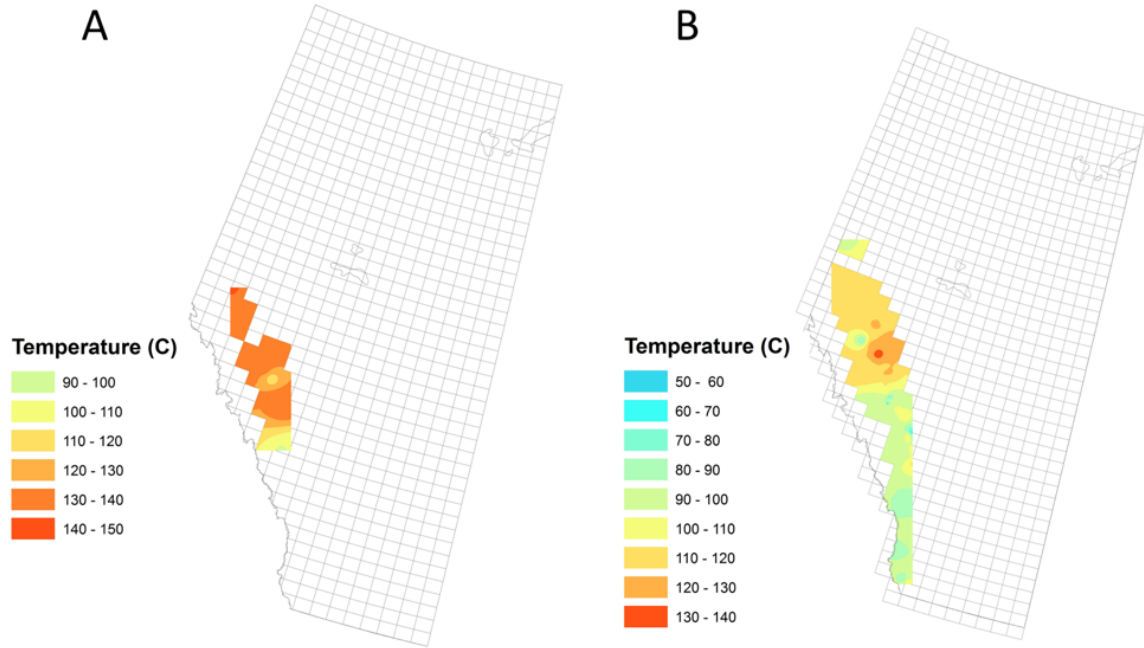


Figure 4.13: Temperatures present at (A) 5500 m and (B) 4500 m for regions in eastern Alberta. The geothermal energy present at these depths can be utilized to generate electricity for small well site power loads or low-temperature process heat.

Geothermal resources also present an opportunity to produce electricity renewably. Conventionally, geothermal energy has been used to power utility scale electricity generation if the resource is hot enough (e.g. in excess of 300 °F, or 150 °C). High quality geothermal resources are present in the United States, primarily in western states such as Nevada, California, and Idaho [79]. The quality of geothermal resources varies by well depth. To achieve sufficient quality of heat, wells often need to be drilled to depths between 3 km to 10 km. provides a look at the geothermal resources in Alberta, Canada, a region relevant to this study. As shown in Figure 4.13, the temperature of the resource does not exceed 150 °C even at a well depth of 5500 m [80]. It is unlikely that the regions considered for this study will be viable

locations to consider using geothermal resources for conventional electricity production. However, reports from this area indicate existing oil and gas production might be co-producing water with temperatures sufficiently high to power thermoelectric generators when wells are drilled to depths greater than 4500 m in the regions highlighted in Figure 4.13. Thermoelectric generators have been utilized by Liu et al to generate electric power with a temperature difference of just 120 °C [81]. These systems could produce 1 kW of electricity, scaled to the power requirements of the control systems discussed within this study, at a cost of approximately \$2,000/kW. This approach might be a unique way to deliver renewable electricity to the well site while leveraging geothermals uniquely reliable nature, unlike the variable electricity production of solar PV and wind.

4.3 Conclusions

The objective of this study was to investigate the potential to replace existing pneumatic control systems and pumps at oil and gas well sites with electrically powered solutions to reduce emissions on-site. Existing pneumatic devices utilize well gas to power their functionality, but in doing so, vent well gas to the atmosphere. Due to the high global warming potential of methane and other well gas constituents, pneumatic devices alone account for approximately 0.4% of all domestic emissions in the United States, based on a carbon dioxide equivalent basis [23]. This study considered two separate designs for replacing the well gas driven pneumatic devices: 1) an all-electric configuration, and 2) an electro-pneumatic configuration that utilizes electricity to power an air compressor that drives the functionality of pneumatic control devices and pumps. To reduce the emissions of these systems, the delivered electricity should be provided by a source with a low emissions intensity. This work considered solar PV, wind, and geothermal (including thermoelectric devices) to generate elec-

tricity on-site. Three separate locations were considered across North America: 1) the Haynesville formation in east Texas, 2) the Permian Basin in west Texas, and 3) the region west of Edmonton, Alberta, Canada.

Analysis was completed to determine how energy storage can improve the reliability of electric and electro-pneumatic devices powered by solar PV. An electric battery with a capacity of 1-2 kWh can deliver nearly 100% reliability for the all-electric configuration utilizing a 200-250 W solar panel for sites located in Texas, resulting in a methane abatement cost of \$190-\$200 per ton of avoided methane emissions. The solar-powered electric system could potentially be employed at a well site in Alberta, Canada. However, ensuring a high level of reliability would be significantly more costly. Other forms of on-site power generation such as geothermal energy might be more viable, or could possibly be used in conjunction with solar PV to ensure reliable operation during the winter when insolation levels are considerably lower. The higher power demands of the electro-pneumatic design require larger PV generation capacity to achieve high levels of reliability. While it is technically and economically feasible for electro-pneumatic systems to utilize compressed air tanks as the primary energy storage medium, electric batteries are the more viable option due to their energy density, stability and relative affordability. However, if the electro-pneumatic design is implemented, well-gas could potentially be used as a back-up to the air compressor to achieve equivalent reliability of the systems currently used in the field. For new well sites, the all-electric option will be more cost-effective. However, if electrification is performed as a retrofit, the electro-pneumatic configuration might be more cost effective if installing the electric system requires more than a week of downtime.

Chapter 5

Conclusions

This dissertation assessed the technical and economical viability of powering brackish groundwater desalination facilities and oil and natural gas well sites with geo-spatially and temporally-varying renewable energy resources. This analysis was performed through the following objectives:

1. Implement a multi-layered geographic information system (GIS) model incorporating spatially-varying brackish groundwater desalination energy intensity and renewable energy availability for the state of Texas.
2. Develop a method to calculate the cost of desalinating brackish groundwater for any given location using data from GIS models as inputs.
3. Create a tool to calculate time-resolved power demands of electrified pneumatic control systems at oil and gas production operations.
4. Assess control equipment, renewable power generation, and energy storage options to reliably match electric loads and economically minimize methane emissions for natural gas well sites located in geographically-disperse North American shale regions.

5.1 Assessing Geo-Spatial Variations in the Techno-Economic Viability of Using Renewable Energy to Power Brackish Groundwater Desalination

Objectives 1 and 2 were explored in Chapter 3 of this dissertation. The work in this chapter developed a novel multi-layered spatial model that integrated different elements of techno-economic performance factors to estimate viability of brackish groundwater desalination powered by wind and solar energy. The model incorporated multiple variables such as depth of water resource, salinity levels, magnitude of local renewable energy resources, distance to water infrastructure, and, for comparative purposes, the local price of water. Brackish groundwater salinity and depth data were collected and interpolated from public well data to assess the geo-spatial variation in the energy intensity of desalination across the state of Texas. The cost of desalinating brackish groundwater with a one million gallon-per-day reverse osmosis facility powered by on-site solar PV or wind electricity generation was then assessed for 1,445 Texas General Land Office sites.

The major findings of the analysis conducted in this chapter were as follows:

1. The energy intensity of brackish groundwater desalination varies from 2 to 20 kilowatt-hours per thousand gallons (kWh/kgal) across the state of Texas when calculated as a function of water depth and salinity.
2. The average water production cost for both wind and solar powered RO facilities is roughly \$5.00/kgal, though wind is generally the lower-cost option due to its higher capacity factor across much of Texas.
3. 193 potentially economically viable sites were identified that have estimated renewable desalination water production costs lower than local municipal water prices.

4. Using wind to power a desalination facility is economically preferable at 145 of the 193 sites; solar was preferable at the remaining 48 sites.

5.2 Assessing the Technical and Economic Viability of Using Variable Renewable Energy to Power Electrified Well Site Pneumatic Systems

The work detailed in Chapter 4 achieved Objectives 3 and 4 of this dissertation. To address Objective 3, an Excel-based energy calculator was developed to serve as a screening tool for well site operators to determine the temporally-varying power demands incurred by switching a standard pneumatic system to an electrified one. To capture the significant site-to-site variation in equipment inventories and power demands, the tool is equipped with a comprehensive set of user inputs. The tool uses these inputs to generate site-specific single-day power loads for electric and electro-pneumatic configurations of well site control systems based on specifications from controllers, valve actuators, and chemical pumps commonly used at well sites. To assess the viability of meeting well site power loads with intermittent renewable energy, electric and electro-pneumatic systems were modeled with solar photovoltaic (PV) power generation and electric battery storage during one year of typical conditions at sites located near Midland, Texas (Permian), Nacogdoches, Texas (Haynesville), and Edmonton, Canada (Kaybob) using a time-resolved energy flow model. The electro-pneumatic model included a thermodynamic analysis to simulate storage of energy as compressed air in addition to electric battery storage.

The major findings of the analysis conducted in this chapter were as follows:

1. The electric control system configuration is generally more energy efficient and cost-effective than the electro-pneumatic system when powered by solar power.

Installing a solar-powered electro-pneumatic system as a retrofit might be more cost-effective if installing the electric system requires more than one week of downtime.

2. When utilizing the electro-pneumatic system, energy can technically be stored primarily as compressed air. However, doing so is not necessarily more cost effective or stable than using electro-chemical batteries as the primary form of energy storage.
3. A battery with a capacity of 1-2 kWh can deliver nearly 100% reliability for the all-electric configuration utilizing a 200-250 W solar panel for sites located in Texas. The solar-powered electric system could potentially be employed at a well site in Alberta, Canada. However, ensuring a high level of reliability would be significantly more costly. Other forms of on-site power generation such as geothermal energy might be more viable, or could possibly be used in conjunction with solar PV to ensure reliable operation during the winter when insolation levels are considerably lower.
4. The cost of avoiding methane emissions was found to be as low as \$190 per ton of methane for a solar-powered electric well site system located in the Permian Basin. None of the methane abatement costs calculated here are lower than the social cost of methane set by the U.S. Environmental Protection Agency in 2018. However, the social cost of methane set by the EPA under the previous administration is greater than the minimized methane abatement costs calculated at all three locations with both electrification configurations.

5.3 Future Work

In Chapter 3, the energy intensity of desalinating brackish groundwater was estimated across the state of Texas by interpolating TDS and depths from well data. However, this interpolation does not account for the possible presence of multiple aquifers at a given location with varying depths and water salinity. Interpolation techniques are also subject to error when spatial data is sparse. Future work should analyze whether the Kriging interpolation technique used here is an appropriate method, or if there are interpolation techniques that will yield more accurate results. The cost and feasibility of drilling source water and disposal wells will also be affected by the geology at a given site. Injection wells for the disposal of produced brine might not be necessary for certain locations as there are currently some inland desalination plants that are able to discharge brine to nearby surface water after receiving approved permits. In a future study, the scope of the analysis could be expanded beyond just discrete Texas General Land Office sites. The analysis could be applied to raster grid across several saline aquifers to give a high-resolution fluid visualization of how the cost of desalination varies geospatially. Finally, future work should also consider a detailed analysis of the temporal variations in renewable power generation, changes in daily and seasonal electricity prices, and ancillary services that a solar or wind powered facility could provide to the electrical grid. If operators are compensated for these services, the net cost of desalination could be further reduced.

In Chapter 4, the study focused on solar PV as an energy source for powering electrified well site control systems and chemical pumps. This framework may be expanded to include other well site equipment such as electric submersible pumps (ESP's), heaters and additional compressors. Utilization of tools such as ESP's might affect the productivity of the well. Future models should factor in how temporal vari-

ations of well productivity will affect power loads. Future work should also seek to identify well site processes with flexible operational schedules to better coincide with intermittent energy sources. The scheduling of certain well site processes could be optimized so that full reliability could be maintained without additional investments in PV power generation and energy storage. Reliability might be maintained more cost-effectively by utilizing more than one source of distributed energy, such as the hybrid PV/fuel cell system developed by Chevron [48]. The methods detailed here can also be applied to assess the viability of utilizing other energy sources with temporally- and geospatially-varying resources. The availability of resources such as solar, wind, and geothermal energy might be highly location-dependent, so the results found at one well site are not necessarily representative of an entire region. A geographic information system could be coupled with the models developed here to assess the viability of electrifying well sites across multiple oil and gas-producing regions. Here we assumed an inventory of well site equipment and power load profiles that is consistent between all three locations and throughout the 10 or 15 year evaluation period. Future research should consider the decrease in power loads over a well's lifetime and regional variations in well site equipment. While power loads vary considerably between wells, some generalized differences could be made for between regions.

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