The Thesis committee for Yael Rebecca Glazer
certifies that this is the approved version of the following thesis:

The Potential for Using Energy from Flared Gas or Renewable Resources for On-Site Hydraulic Fracturing Wastewater Treatment

APPROVED BY

SUPERVISING COMMITTEE:

____
Michael E. Webber, Supervisor

____
Daene McKinney

The Potential for Using Energy from Flared Gas or Renewable Resources for On-Site Hydraulic Fracturing Wastewater Treatment

by

Yael Rebecca Glazer, B.S.

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To my husband who supports me unconditionally in all my endeavors, including my journey through graduate school. Many thanks to my parents who always emphasized the importance of a good education and hard work, and are forever proud of my achievements.

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The Potential for Using Energy from Flared Gas or Renewable Resources for On-Site Hydraulic Fracturing Wastewater Treatment

Yael Rebecca Glazer, M.S.E.
The University of Texas at Austin, 2014

Supervisor: Michael E. Webber

The oil and gas well completion method of hydraulic fracturing faces several environmental challenges: the process is highly water-intensive; it generates a significant volume of wastewater; and it is associated with widespread flaring of co-produced natural gas. One possible solution to simultaneously mitigate these challenges is to use the energy from flared natural gas to power on-site wastewater treatment, thereby reducing 1) flared gas without application, 2) the volumes of wastewater, and 3) the volumes of freshwater that need to be procured for subsequent shale production, as the treated wastewater could be reused. In regions with minimal flaring a potential solution is to couple renewable electricity (generated from solar and wind energy) with on-site wastewater treatment, thereby 1) reducing the volumes of wastewater, 2) reducing the volumes of freshwater that need to be procured for subsequent shale production, and 3) displacing fossil fuel energy for treatment. This study builds an analytical framework for assessing the technical potential of these approaches. In this research, the hydraulic fracturing wastewater characteristics (such as quality, quantity, and flow rates) were considered along with various treatment technologies best suited to utilizing natural gas and renewable electricity, using the Permian Basin in west Texas as a geographic test bed for analysis. For the analysis looking at using flared natural gas energy for on-site treatment, the required volume of gas to meet the thermal energy requirements for treatment was calculated on a per-well basis. Additionally, the volume of product water (defined here as the treated water that can be reused) based on the technology type was determined. Finally, the theoretical maximum volume of product water that could be generated using the total volume of natural gas that was flared in Texas in 2012 as a benchmark was calculated. It was concluded that the thermal energy required to treat wastewater that returns to the surface over the first ten days after a well is completed is 140–820 Million British Thermal Units (MMBTU) and would generate 750–6,800 cubic meters of product water depending on the treatment technology. Additionally, based on the thermal technologies assessed in this study, the theoretical maximum volume of product water that can be generated statewide using the energy from the flared gas in 2012 is 180–540 million cubic meters, representing approximately 3–9% of the state's annual water demand for municipal purposes or 1–2.4% of total statewide water demand for all purposes [1]. This is enough gas to treat more water than was projected would be used for the entire mining sector in 2010 in Texas [1]. For the analysis coupling renewable electricity with on-site treatment, the necessary energy for water management upstream and downstream of a well site was calculated and compared with the current energy requirements and those of a proposed strategy where a portion of the wastewater is treated on-site and reused on a subsequent well. Through this analysis, it was determined that implementing on-site treatment using renewable electricity could reduce freshwater requirements by 11–26%. Finally, it was calculated that this approach could displace approximately 16% of the fossil fuel energy requirements for pumping freshwater, trucking that water to the well site, and trucking wastewater to a disposal well.

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Chapter 1

Introduction

Following several decades of stagnant growth, natural gas production in the United States has experienced a steady increase from 19 trillion cubic feet (TCF) in 2005 to almost 26 TCF in 2013 and is projected to further increase by approximately 38% by 2040 [5]. This steep rise in domestic production is due in large part to the recent expansion of natural gas extraction from the abundant shale resources made economically feasible through technological improvements in hydraulic fracturing and horizontal drilling. Figure 1.1 shows the historical and projected trends for domestic natural gas production by type and depicts the growth in overall production resulting mainly due to a rise in shale gas production.

Natural gas is a critical component to the overall energy mix in the U.S. and, along with oil and coal, it is one of the three main fossil fuels used as primary energy. In 2011, natural gas accounted for 25% of the primary energy consumed in the U.S. second only to oil which accounted for 36% of the nearly 100 quadrillion British Thermal Units (Quads) of energy consumed [19].

Compared to oil and coal, natural gas burns cleaner, emitting significantly lower levels of criteria pollutants such as carbon monoxide, carbon dioxide, and sulfur dioxide. For example, for every MMBTU of energy produced, natural gas emits 117 pounds of CO_2 while gasoline and lignite coal emit 157.2 and 215.4 pounds of CO_2, respectively [20]. As such, natural gas is often considered a more desirable fossil fuel than coal or oil from a greenhouse gas emissions perspective.

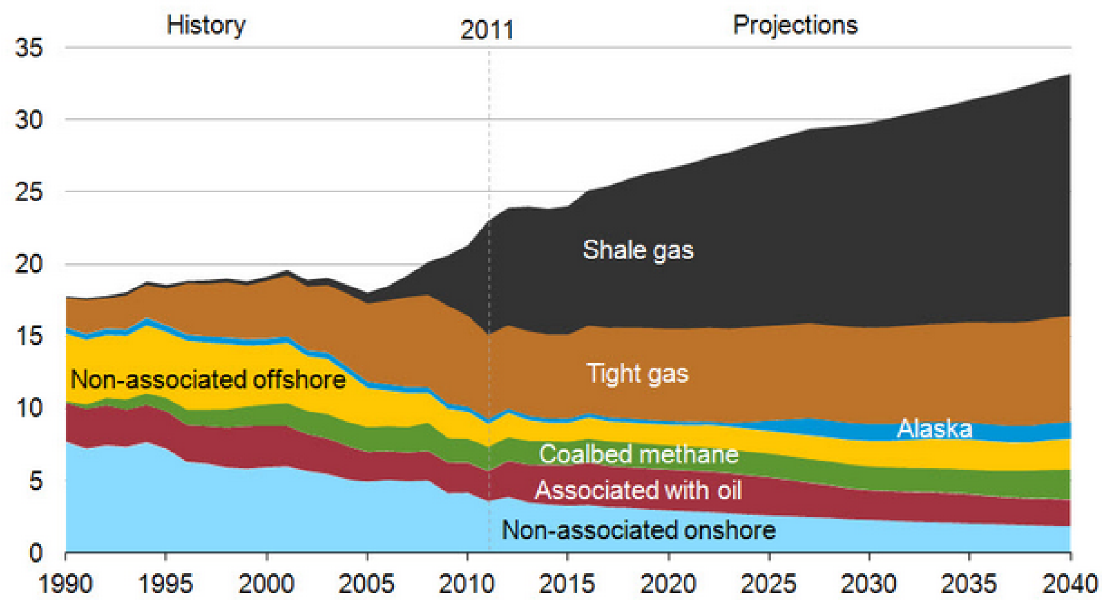


Figure 1.1: This graph shows historical and projected dry natural gas production by type in the U.S. in trillion cubic feet (TCF) [5].

Aside from its environmental benefits, several economic and political drivers served as impetuses to increase domestic production of the abundant shale oil and gas resource. First, an increase in domestic energy production and supply means a reduction in U.S. dependence on foreign energy—a goal that has been articulated by American presidents and other politicians for decades. Second, development of shale regions means the creation of thousands of U.S. jobs, another strong political consideration that is often emphasized during periods of economic recession.

Despite the environmental benefits natural gas combustion offers over coal and oil, and the various economical and political drivers for increasing its production, the shale oil and gas extraction process creates several environmental challenges. First, there are the concerns surrounding the water use. In hydraulic fracturing ("fracking"), millions of gallons of (typically fresh) water are mixed with chemicals and proppant (often sand) to generate a fracturing fluid ("frac fluid") that is injected at high pressures into the well to induce fissures in the shale formation [3].

Second, there are concerns regarding wastewater generation and disposal methods. In shale regions in Texas, the estimated wastewater (comprised of flowback and produced water) that will return to the surface relative to the initially injected fluid ranges from 15% to over 200% over the lifetime of the well [2]. In Texas, this wastewater, which often contains contaminant levels and total dissolved solids (TDS) concentrations that exceed the capabilities of industrial treatment facilities, is typically trucked to a deep well injection (DWI) site for disposal, effectively sequestering it from future use. Meanwhile, many regions in the southern and midwestern U.S. with escalating hydraulic fracturing activity are also often subject to drought or water-stressed conditions, making the industry's water use and wastewater disposal impactful and an exacerbating driver of water scarcity in those regions [21]. Other regions, such as the Marcellus shale in the northeastern U.S., lack an adequate number of injection wells, potentially increasing disposal costs due to longer trucking or piping distances [22].

Third, there are concerns regarding the wasted energy and emissions from flaring natural gas associated with shale production. For example, approximately 30% or more of the natural gas extracted from the Bakken Shale in North Dakota is flared, and in Texas, the percentage of the total statewide natural gas production that is flared has increased six-fold between 2007 and 2013 from approximately 0.1% to 0.6% of total statewide gas production [18,23]. It should be noted that despite the effort to flare most of the natural gas that is not moved to market, a fraction is often still vented unburned due to potential leaks on-site and imperfect burn efficiencies [24]. Venting and leaks are considered less desirable than flaring since the methane in unburned natural gas is a more potent greenhouse gas than the carbon dioxide, which is emitted after combustion.

One potential solution that could simultaneously mitigate these three environmental concerns is to produce freshwater via on-site treatment of wastewater by use of recovered natural gas that would otherwise be flared. Thus, this proposed approach couples and reduces two waste streams (wastewater and flared gas), transforming them from two environmental liabilities into a valuable commodity of treated water that can be reused at a subsequent production site. Another potential solution is to couple renewable energy resources with wastewater treatment in shale regions with abundant solar or wind energy. Using renewable energy in areas with little to no flaring means displacing fossil fuels for wastewater treatment. Implementing one of these strategies could reduce the oil and gas industry's demand for local water supplies and the number of truck-miles required to transport water and wastewater to and from the well site.

The goal of this work is to establish an analytical framework for 1) assessing the extent to which on-site treatment of wastewater using recovered natural gas or renewable resources is technically feasible, 2) calculating the potential water savings realized, and 3) determining the energy required by implementing one of these strategies. This analysis focuses on the Permian Basin, located in West Texas, as a geographic test bed because of its relative water scarcity and its rampant production over the last several years.

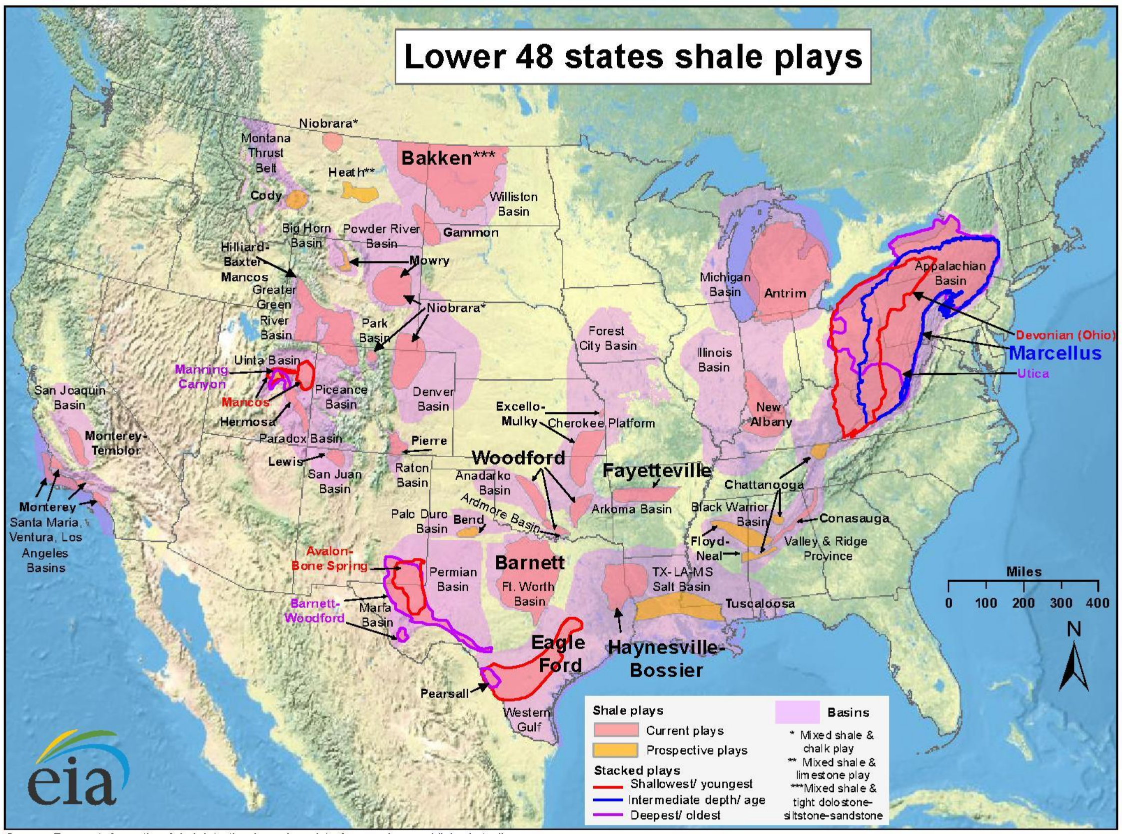
Chapter 2

Background

Between the mid-1980s and the mid-2000s, crude oil and gas imports saw a steady increase in the U.S., reaching a high of 3.7 billion barrels of crude oil in 2005 and 4.6 trillion cubic feet (TCF) of gas in 2007 [25, 26]. However, over the last five to seven years, imports have gradually decreased each year with future projections continuing the downward trend. There are several factors that help explain this directional shift in U.S. oil and gas import trends including 1) a decline in overall energy consumption in the U.S., 2) a significant economic recession in 2008, and 3) likely the main driver, the recent and rapid expansion of domestic shale oil and gas production. Given the extensive growth in domestic shale production it is often termed "The Shale Revolution" [27]. The development of domestic shale resources has led to a drop of net imports of natural gas in the U.S. by 23% in 2012 alone aiding to the decrease in the U.S.'s overall dependence on foreign energy [25]. The U.S. Energy Information Administration (EIA) estimates that the technically recoverable amount of shale resources in the U.S. are approximately 58 billion barrels of oil and 665 trillion cubic feet (TCF) of gas [28]. Figure 2.1 shows the location for the shale resources in the U.S.

2.1 Shale Oil and Gas Extraction Process

Shale oil and gas extraction begins with a vertical well drilled thousands of feet to the shale formation. Once the drill reaches the formation, the drill bit is often



Source: Energy Information Administration based on data from various published studies.
Updated: May 9, 2011

Figure 2.1: This map shows the location for the shale plays and basins in the lower 48 states [6].

turned horizontally, and drilling continues for several thousands of feet to increase the well contact with the shale formation. After the well has been drilled, millions of gallons of water mixed with proppant (often sand) and chemical additives, known as frac fluid, are injected at high pressure to induce fissures in the shale formation in a process called hydraulic fracturing or fracking [3]. Much of the proppant remains within these cracks to keep them "propped" open to allow the oil and gas to flow into the well and then to the surface. A percentage relative to the volume of the initially injected fluid will return to the surface as wastewater and often includes flowback and produced water (along with drilling muds).

2.2 Environmental Concerns With Hydraulic Fracturing

As hydraulic fracturing has become more prevalent in the U.S., researchers have published numerous studies on its associated environmental and social challenges often including potential ways for mitigating these impacts. These challenges include the water use, generated wastewater, on-site natural gas flaring, and increased truck traffic in the local communities, among others.

2.2.1 Water Use and Generated Wastewater

A range of 3–8 million gallons of water per well is required for hydraulic fracturing [2]. The water used for hydraulic fracturing is often sourced from nearby surface water or groundwater and is either trucked or piped to the well site. The generated wastewater often has one of three fates:

1. Being trucked or piped to a deep well injection site for disposal.

2. Being trucked or piped to a municipal treatment facility.

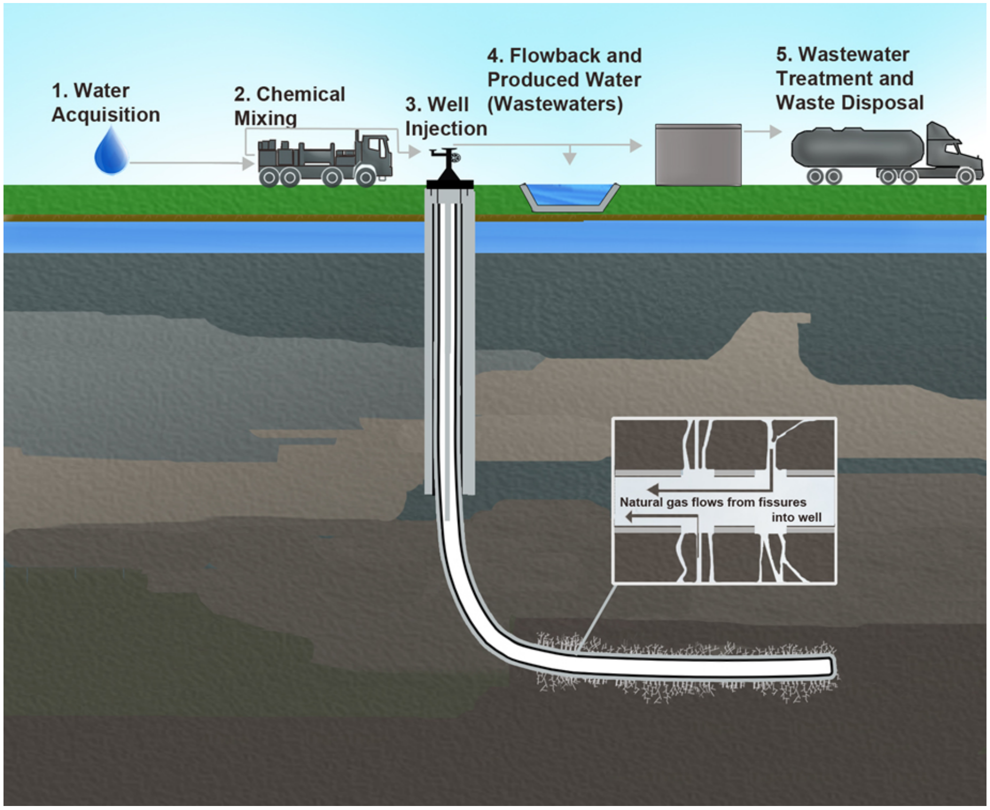


Figure 2.2: This figure depicts the hydraulic fracturing process from water acquisition to wastewater removal. While the picture shows the process including wastewater treatment and waste disposal, in Texas, the vast majority of the wastewater is trucked or piped to nearby disposal wells and does not undergo any treatment. Wastewater treatment is more prevalent in shale regions located in the northeastern U.S. [7] Note: Figure not drawn to scale.

3. Being treated on-site likely for the reuse at a nearby well.

Figure 2.2 depicts the overall hydraulic fracturing process and its associated water acquisition and removal.

Nicot, *et al.* conducted an in-depth analysis into the current and projected water use for oil and gas extraction in Texas and also included information on the typical amounts of wastewater generated by shale regions in the state [2]. They found that water use for hydraulic fracturing in Texas has increased from approximately

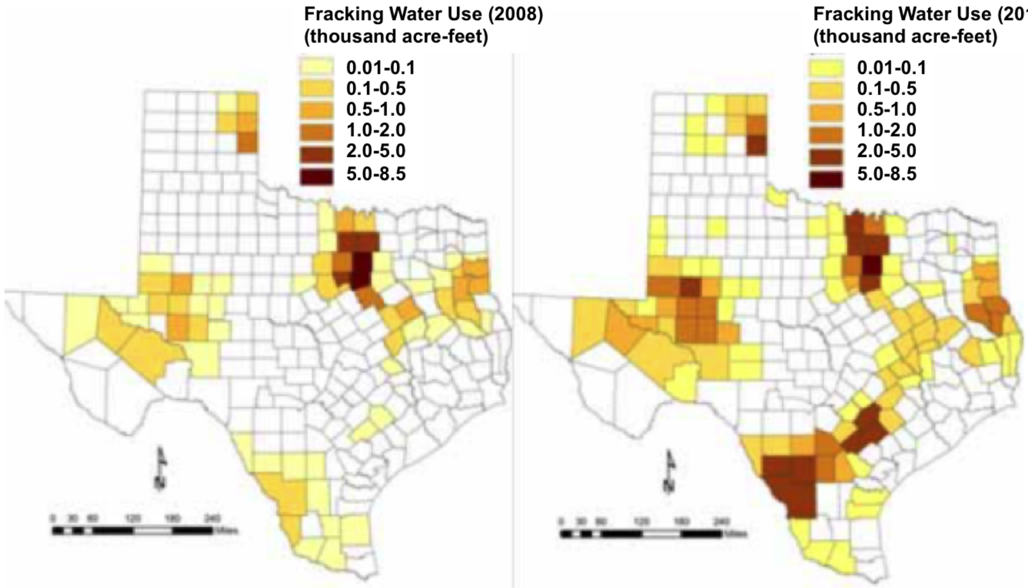


Figure 2.3: This figure shows the rise in water use for hydraulic fracturing by county in Texas between 2008 and 2011 [2].

44,400,000 m^3 in 2008 to 100,500,000 m^3 in 2011 an increase of almost 2.5 times the water use in three years. They also determined that in many regions in Texas, water use per well has also increased over the same time period. From their study, the annual water use for fracking is projected to peak sometime in the 2020's around 154,000,000 m^3 and then begin to slowly decline with projected annual use around 50,000,000 m^3 in 2060. Figure 2.3 shows the increase in water use by region in Texas for hydraulic fracturing between 2008 and 2011.

The map in Figure 2.4 shows the U.S. drought conditions from May 3, 2011 with an overlay of the U.S. shale regions. The map reveals that many shale regions in the south and midwest experienced some level of "moderate" to "exceptional" drought conditions. Taking a closer look at drought in Texas for that same time period, Figure 2.5 shows that virtually the entire state experienced some level of water scarcity from "abnormally dry" to "exceptional" drought. During that time, the majority of the Permian Basin region experienced "extreme" to "exceptional" drought.

Shale regions located in the northeastern U.S., such as the Marcellus shale, often have ample water supplies but face challenges with wastewater disposal via deep well injection. Many producers in these regions have already shifted toward some level of on-site treatment of at least a portion of their wastewater to help reduce disposal costs [29].

Water resources in many regions will likely become more scarce due to drought and increasing competition among users. As such, many producers are looking for alternative water sources to surface water and groundwater [30]. Many are moving towards using more brackish water, effluent from local municipal treatment facilities, or recycling and reusing their own wastewater [2]. Despite this trend, the industry currently still relies heavily on freshwater resources [2].

2.2.2 Wastewater Characteristics

Hydraulic fracturing wastewater is often made up of drilling muds, flowback water, and produced water. Drilling mud is used during the drilling of the well and some percentage of those muds will return to the surface and require disposal. Flowback water is the fluid that returns to the surface in the first several weeks following well completion and is generally understood to be comprised mostly of the initially injected frac fluid [31]. Produced water is the fluid that generally comes to the surface later on during oil and gas recovery from the well and consists of water and naturally occuring chemicals found in the formation [32]. Produced water is typically "dirtier" than flowback water having a higher TDS concentration and might also contain higher levels of undesirable contaminants such as naturally occurring radioactive material (NORM) such as radium [32]. The exact constituents of the

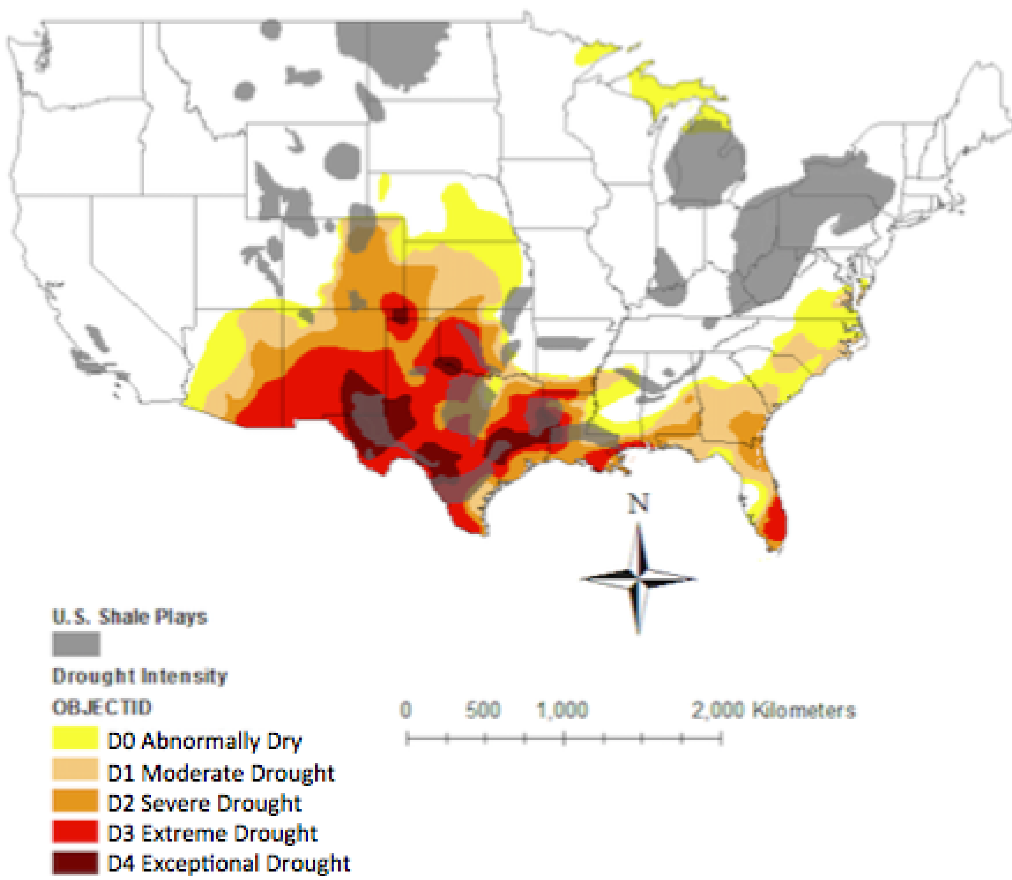


Figure 2.4: This map shows U.S. drought conditions for May 3, 2011 with an overlay of the shale regions revealing many areas where drought conditions and shale resources coincide (primarily in the south and midwest) [8, 9].

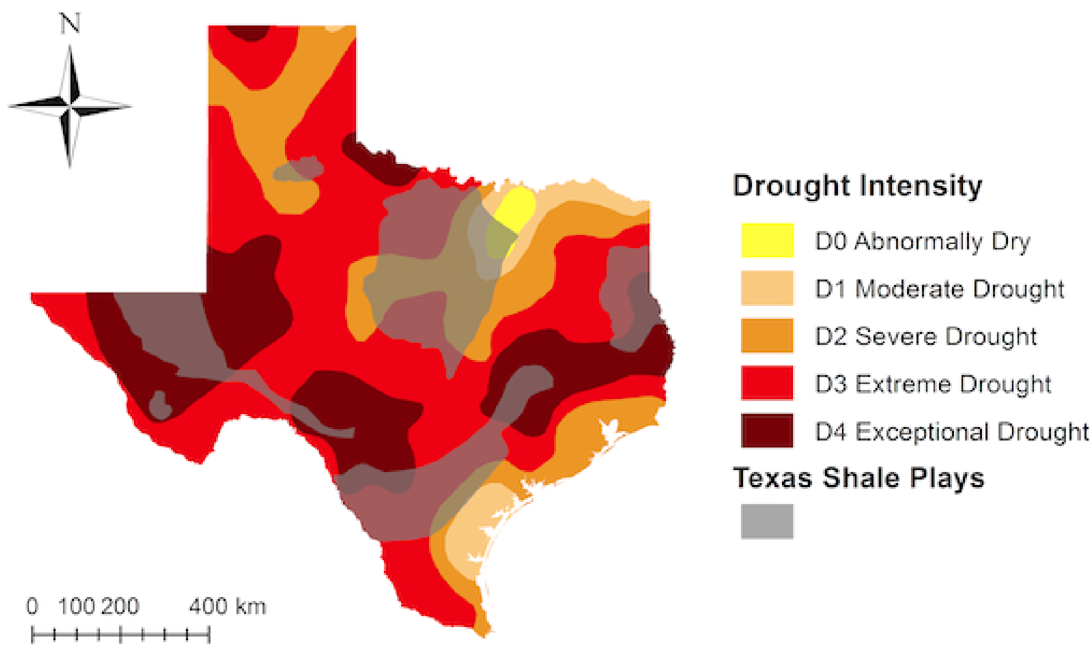


Figure 2.5: This map of Texas shows the drought conditions from May 3, 2011 with an overlay of the shale regions revealing that much of the state experienced some level of drought during this time period. The Permian Basin, located in west Texas, experienced "extreme" to "exceptional" drought conditions during this time [8, 9].

Table 2.1: Summary of the estimated percentage of wastewater (flowback and produced water) generated relative to the initially injected volume of frac fluid by shale region in Texas [2].

Play/Region	Ratio of Wastewater to Injected Frac Fluid
Delaware Basin (Permian Basin)	Close to 100% in year 1, 150% well life, >200% well life
Midland Basin (Permian Basin)	80%–100% in year 1
Andarko Basin	50% in month 1, 90% at month 6
Barnett Shale	10–20% month 1, 20–60% well life, 70% year 1, 150% in 5 years
Eagle Ford Shale	20% over life
Haynesville Shale	20% over life, 15% over life
Cotton Valley FM	60% month 1, >100% well life, 40% or 100% over life

produced water depend significantly on the shale formation.

The volume of wastewater that returns to the surface can vary greatly from one shale region to another and depends significantly on the geology of the formation being fractured and the production process implemented. For example, Table 2.1 summarizes the estimated wastewater generated per well as a percentage of the volume of frac fluid initially injected for shale plays in Texas. This table reveals the wide range of expected wastewater depending on the shale formation.

As previously mentioned, today in Texas the vast majority of the generated wastewater is either trucked or piped to deep well injection sites, essentially removing the water from the hydrologic cycle and thus from any future use. Disposing of wastewater in this fashion in already water-stressed regions could potentially further intensify the water scarcity in those areas. While water use for hydraulic fracturing

Table 2.2: This table shows that water use for fracking on a county-level can be much higher than the overall water use for fracking statewide reaching as high as 29% in Johnson County. It should be noted that these values are for 2008 and water use for fracking as a percentage of total water use has likely significantly changed (and likely increased) since then. [3]

Shale Region	County	Percent of total net water use in 2008 used for shale gas production
Barnett	Denton	2.8
	Johnson	29
	Parker	10
	Wise	19
Eagle Ford	Dimmit	0.1
	La Salle	0.1
Texas Haynesville	Harrison	0.2
	Panola	0.5

is significant, it accounts for less than 1% of total water demand in Texas. On a local level, however, water use for fracking can be much greater. Table 2.2 reveals water use for fracking is significantly higher in certain counties compared to the state as a whole.

2.2.3 Natural Gas Flaring

Flaring is the process of intentionally burning natural gas and is often employed at oil and gas production sites, oil refineries, and natural gas processing plants. This technique is done for safety reasons and to reduce the amount of methane (making up 70–90% of natural gas), a more potent greenhouse gas than carbon dioxide, that is released into the atmosphere. Methane combustion converts methane into carbon dioxide through a series of steps with the net result represented in Equation 2.1.

$$CH_4 + 2O_2 \longrightarrow CO_2 + 2H_2O \tag{2.1}$$

At oil and gas production sites, flaring is most prevalent in regions where oil and gas are co-produced and where pipeline infrastructure is insufficient to collect and transport the gas to market. This shortcoming leaves the producer with several options in these regions including building gas pipeline or other gathering infrastructure, flaring the gas, or using the gas on-site. In the absence of pipelines, beneficially using the gas on-site might be appealing.

Meanwhile, in regions where gas pipelines are built or already exist, technologies allowing for the capture of natural gas that would otherwise be flared are often implemented by producers [33]. In these regions, producers might decide to divert a portion of their natural gas to power on-site water treatment.

Texas does not require a permit to flare gas for the first ten producing days after initial completion or re-completion of the well [18]. If a producer determines flaring is required beyond the initial ten days, a permit must be obtained from the Railroad Commission of Texas (RRC), the state's regulatory agency that oversees oil and gas activity in Texas. Permits are issued for 45 days at a time with a maximum limit of 180 days. Flaring rules and regulations are detailed in the RRC's Statewide Rule 32. Those flares—when they occur—are regulated for cleanliness by the Texas Commission on Environmental Quality (TCEQ).

2.2.4 Trucking

A tremendous number of truck trips are required to haul the required equipment, water, and chemicals to and from the well site for the hydraulic fracturing operations. The Center for Transportation Research at The University of Texas determined that bringing a single well to production requires 1,184 loaded trucks increasing truck traffic in many communities that have expanding oil and gas production [34]. Many of these regions do not have roads that support the weight and number of large trucks causing an average overall impact on pavement life reductions of approximately 30% [34]. Additionally, these trucks have been blamed for increasing noise pollution, air pollution, and road accidents.

2.2.5 Additional Environmental and Social Concerns

There are many additional concerns associated with hydraulic fracturing including land disturbances, risk of wastewater spills and groundwater contaminations, induced seismicity of regions surrounding wastewater disposal sites, and even increased homelessness and alcohol related crimes in nearby communities. While these are significant concerns, this research mainly focuses on and addresses the concerns raised in Sections 2.2.1 through 2.2.4.

2.3 Wastewater Treatment

A wide range of technologies exist for treating hydraulic fracturing wastewater and each one has tradeoffs in terms of energetic requirements, economics, effectiveness at removing different contaminants, and portability. A producer that decides to treat their wastewater must weigh the pros and cons of the available technologies to determine which is best suited for their specific situation and needs. Some might choose a technology that performs the minimum level of treatment for reuse thus potentially saving energy, time, and often cost, compared to technologies that treat to higher product water quality standards. Many researchers including Drewes, *et al.* and Igunnu, *et al.* have assessed the variety of treatment technologies available for treating wastewater by many criteria including the energy requirements, feed water quality, product water quality, recovery rate (defined as the volume of product water to volume of starting feedwater), and infrastructure considerations [16,35]. The treatment technologies they evaluated can be classified into the following categories:

- Basic Separation
- Membrane Separation
- Thermal Technologies
- Adsorption
- Oxidation and Dissinfection
- Enhanced Distillation and Evaporation
- Enhanced Pressure Driven

They assessed many technologies within each classification including membrane separation technologies such as reverse osmosis and microfiltration, and thermal technologies such as multi-effect distillation and vapor compression, among many others. The wide variety of available treatment options allows producers to pick the most ideal technology to match their specific water treatment goals.

2.4 Renewable Resources

Aside from potentially using recovered natural gas and other fossil fuels such as diesel to power on-site treatment, another possible option is to harness renewable energy resources including solar and wind that might be available on-site to provide the required energy for treatment. The ability to use solar or wind generated electricity for on-site treatment depends heavily on the location of the shale region. Figure

2.6 shows a map of the U.S. annual average direct normal solar irradiance with an overlay of shale regions revealing that many of the shale plays located in the mid-western and southern U.S. have a significant level of insolation. Taking a closer look at Texas, Figure 2.7 reveals annual solar radiation is fairly high across the state and especially strong in the Permian Basin with average values ranging from 5.5 to 6.6 kWh/m^2/day.

Figure 2.8 shows the annual average U.S. wind power classifications at a height of 50 meters with an overlay of the shale plays revealing wind power are highest in a vertical band in the midwest spanning many shale regions including the Bakken Shale in North Dakota down to the Permian Basin in west Texas. Figure 2.9 shows the annual average wind power classifications with the shale plays overlaid for Texas revealing significant wind power is located in west Texas. This might make wind energy an option in the Permian Basin.

2.5 Permian Basin as a Case Study

The Permian Basin is located in west Texas and spans an area approximately 250 miles wide and 300 miles long [12]. The region has been active in conventional oil and gas production since 1921, and recent exploration has revealed a significant amount of shale oil and gas that can be feasibly extracted [12]. As such, the region is currently undergoing a boom in shale oil and gas production. Figure 2.10 shows the Texas counties located in the Permian Basin. Figure 2.11 shows the location of the Permian Basin relative to Texas and New Mexico as well as its major boundaries and subdivisions.

In contrast to its energy abundance, the Permian Basin is water-scarce. Average annual precipitation for Midland, a city in this semi-arid to arid region, is only

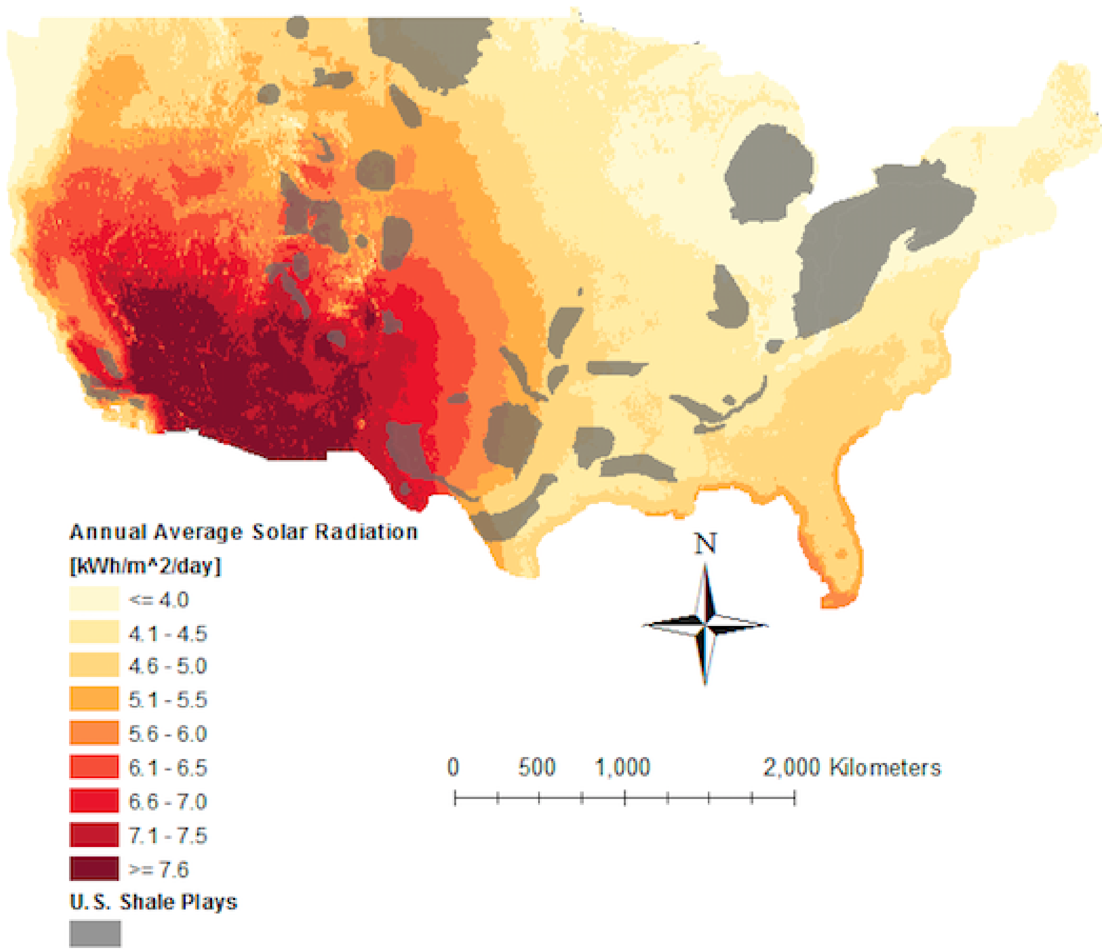


Figure 2.6: This map shows the U.S. direct normal solar radiation with an overlay of the shale plays revealing many regions with significant amounts of shale oil and gas coincide with areas that receive considerable insolation [10].

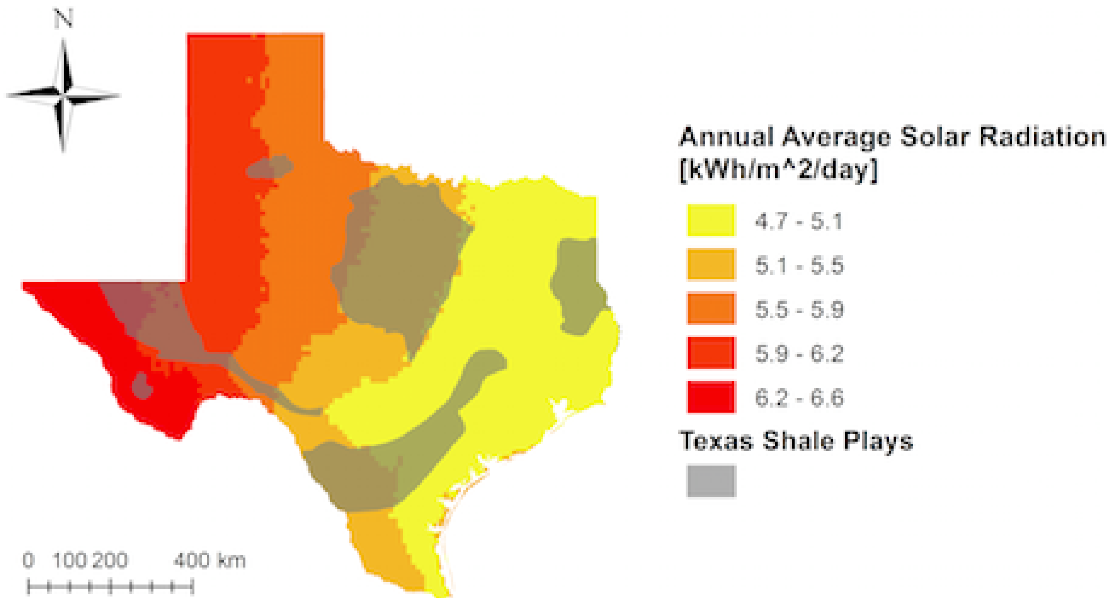


Figure 2.7: This map shows the location of the Texas shale regions with an overlay of the direct normal solar radiation energy source revealing many regions with significant amounts of shale oil and gas coincide with areas that receive considerable insolation. The Permian Basin receives an annual average solar radiation between 5.5 to 6.6 kWh/m^2/day [10].

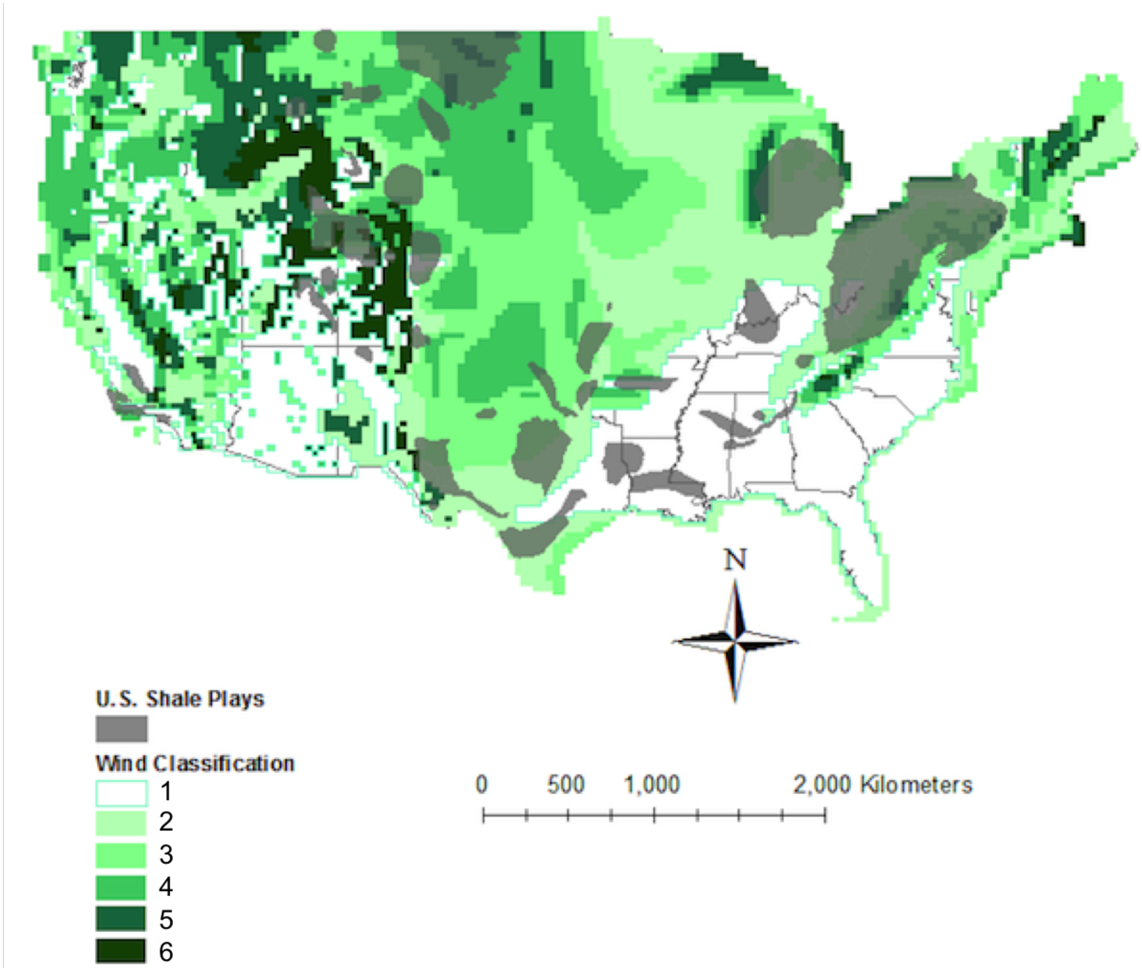


Figure 2.8: This map shows the U.S. annual average wind power classifications with an overlay of the shale regions. The map reveals that many shale plays in the vertical band from North Dakota down to Texas coincide with significant wind power [9, 11].

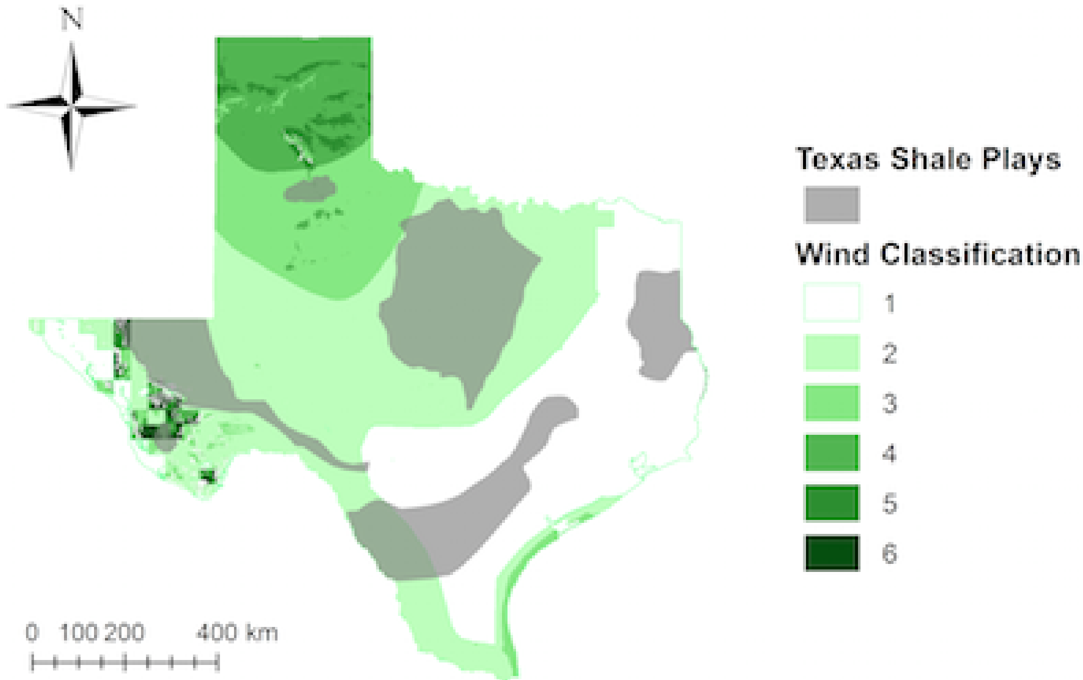


Figure 2.9: This map shows the annual average wind power classifications with an overlay of the shale regions in Texas revealing that the north and west regions of Texas experience relatively high wind speeds [9, 11].

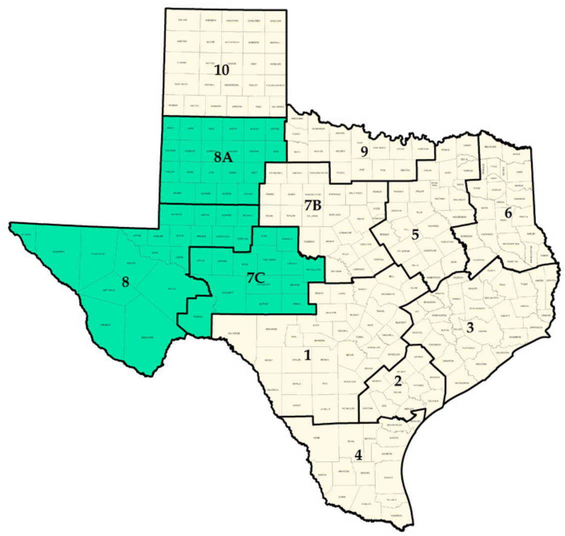


Figure 2.10: A map of the Texas counties located in the Permian Basin [12].

14.6 inches [36]. An expansion of fracking activity in the region will mean an increase in water demands by the oil and gas industry. This rise in demand, alongside projected population growth, could further exacerbate water scarcity in this part of Texas. As such, reduction in water use by the industry might be a key component of mitigating water constraints in the region.

Water for fracking in the Permian Basin is sourced almost entirely from nearby groundwater aquifers and is trucked or piped to the well site [2]. Due to its geology, wastewater volumes as compared to the initially injected water can be as high as 100% in the first year to over 200% over the lifetime of the well [2]. This wastewater is then often trucked or piped to deep well injection sites for disposal. These high wastewater volumes coupled with water scarcity suggest the Permian Basin as a good candidate for wastewater recycling and reuse.

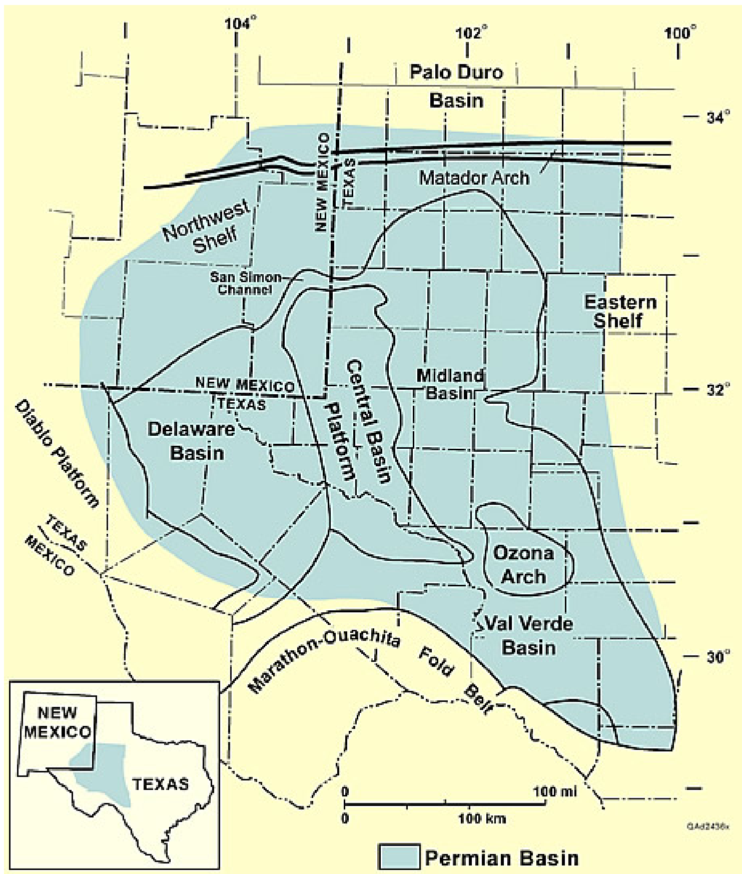


Figure 2.11: This map shows the location of the Permian Basin relative to Texas and New Mexico as well as its major boundaries and subdivisions [13].

2.6 Research Goals

To the author's knowledge, no one has conducted an in depth analysis that examines either the potential for 1) integrating flared gas for wastewater treatment or 2) coupling renewable energy resources for treating wastewater from shale production. This work seeks to fill that knowledge gap.

.

Chapter 3

Key Technical Considerations for Treating Hydraulic Fracturing Wastewater

As mentioned previously, wastewater generated from oil and gas production typically has one of three fates that include being 1) trucked or piped to a disposal well, 2) trucked or piped to a nearby municipal wastewater treatment facility, or 3) treated on-site largely for the purpose of reuse at a nearby well. There are many considerations producers take into account when assessing which of these paths to choose including (but not limited to):

- Local water availability
- Wastewater disposal versus treatment costs
- Availability of disposal wells
- Energy source for treatment and associated costs
- Wastewater charactistics and anticipated difficulty to treat
- Level of treatment desired and applications for product water
- Availability of municipal treatment facilities
- Existing infrastructure such as pipes for water and wastewater transportation
- Current and anticipated future local, state, and federal policies

It should be noted that many of these factors are interrelated. For example, treatment cost is dependent on the level of treatment desired and the starting wastewater characteristics. This chapter highlights and discusses some of the key technical variables and considerations of implementing some level of on-site wastewater treatment using either natural gas or renewable energy.

3.1 Wastewater Characteristics

The amount of water required to fracture a well and the percentage of water that will return to the surface as wastewater will vary depending on the production process that is implemented and the geology of the formation being fractured. The quality of the wastewater will vary not only with the geology of the formation but also with the composition of the fracturing fluids injected. These characteristics are fundamental factors in determining the most cost-effective volume of wastewater to treat. It is fairly straightforward to obtain per-well water use data in Texas either through FracFocus, a public access website documenting producer-reported chemical and water use, or through published studies detailing median and average water use by region [2,37]. Data on wastewater quality and flow rates are rarely reported or published and, as such, are more difficult to obtain. However, it is generally understood that wastewater flow rate starts out high with a relatively low TDS concentration; over time, the flow rate drops significantly while the TDS concentration increases substantially [38]. Figure 3.1 shows the wastewater characteristics of a recently fractured well over the first 120 days after well completion. Figure 3.2 shows the the wastewater characteristics for the same well over the first 40 days after well completion. These trends, demonstrated in the figures, are significant because depending on the treatment technology implemented, the energy intensity may increase while the recovery rate drops with rising TDS levels. Thus, as time goes on, treating the

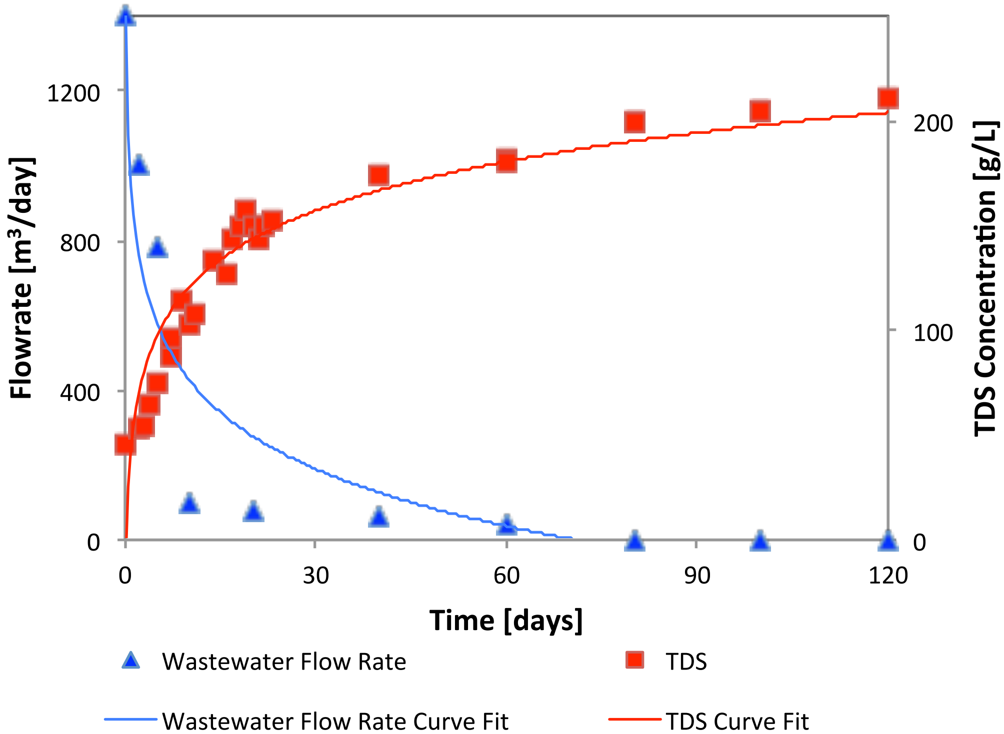


Figure 3.1: This figure shows data and the logarithmic fitted curves, for TDS concentration and hydraulic fracturing wastewater up to 120 days after the well is drilled [14]. In general, flow rates from shale production sites generally decrease with time (starting in days after initial production) while TDS levels increase over time and both trends plateau after approximately 60 days. Exact values vary from well to well and from field to field but the overall trends are nominally similar.

wastewater could yield diminishing returns while potentially requiring greater energy intensity for treatment.

3.2 On-site Wastewater Treatment Technologies Assessed

Given the desire to first analyze the potential for using natural gas as the energy source for treating the wastewater, thermal treatment options were considered including multi-stage flash distillation (MSF), multi-effect distillation (MED), me-

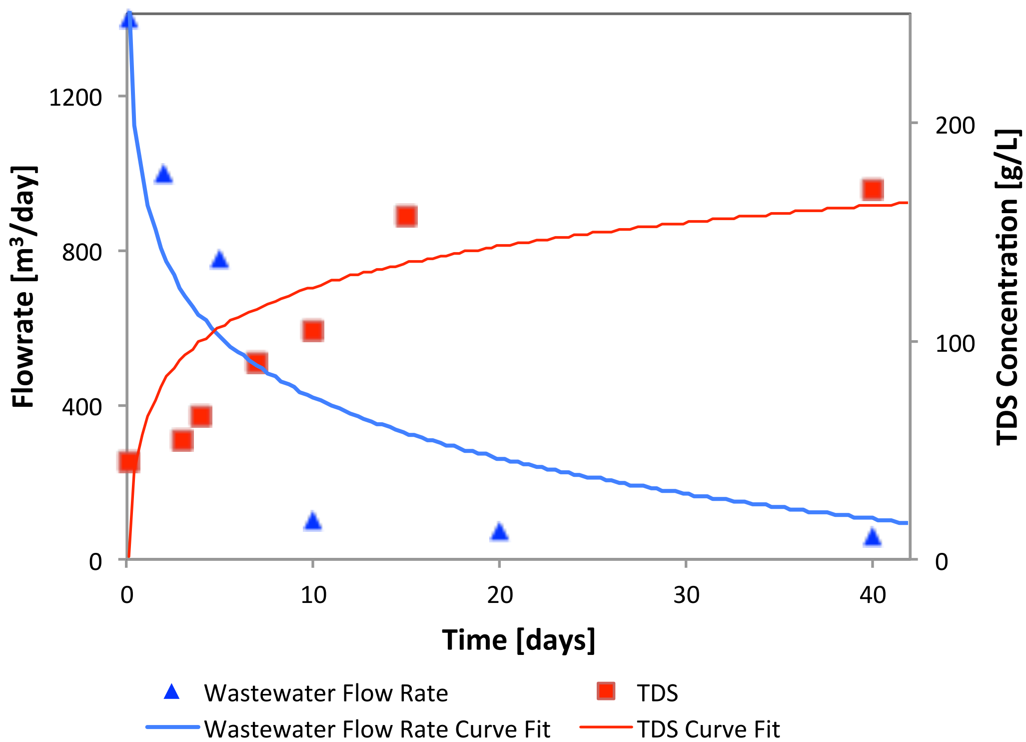


Figure 3.2: This figure shows data and the logarithmic fitted curves, for TDS concentration and hydraulic fracturing wastewater up to 40 days after the well is drilled [14]. In general, flow rates from shale production sites generally decrease with time (starting in days after initial production) while TDS levels increase over time. Exact values vary from well to well and from field to field but the overall trends are nominally similar.

chanical vapor recompression (MVR) evaporation, and membrane distillation (MD) for coupling treatment with recovered natural gas. Reverse osmosis (RO) was the main technology assessed for use with renewable energy resources.

MSF, MED, and MVR were chosen for analysis because of their minimal pre-treatment requirements, ability to tolerate high TDS concentrations common in hydraulic fracturing wastewater, and the high quality of the product water [16]. The energy required for treatment using the thermal technologies is independent of the starting TDS concentration of the wastewater [39]. Notably, these technologies are often more energy-intensive than many available membrane treatment options [16]. This tradeoff seems appropriate for two reasons. First, treating to very high product water quality (often as low as a TDS concentration of 2-10 mg/L) gives producers more options for beneficial reuse than lower quality water [16]. Second, these treatment technologies can more readily use on-site natural gas as their energy source that is otherwise potentially being unused and wasted.

Membrane distillation was also included in this analysis due to the fact that it is an emerging technology for this particular application. However, because it is relatively new, minimal information and data regarding energy use and water recovery for MD are currently available. The following is a high level explanation of the four different thermal treatment technologies assessed and Table 3.1 summarizes their energy intensity and typical recovery rates.

3.2.1 Multi-Stage Flash Distillation (MSF)

MSF is a thermally-driven water treatment technology. As its name suggests, it distills water by flash evaporation, a method where the pressure is lowered so that evaporation can occur at lower temperatures [15]. There are often many stages where water is flashed, each comprising of a heat exchanger and a condensate collector and

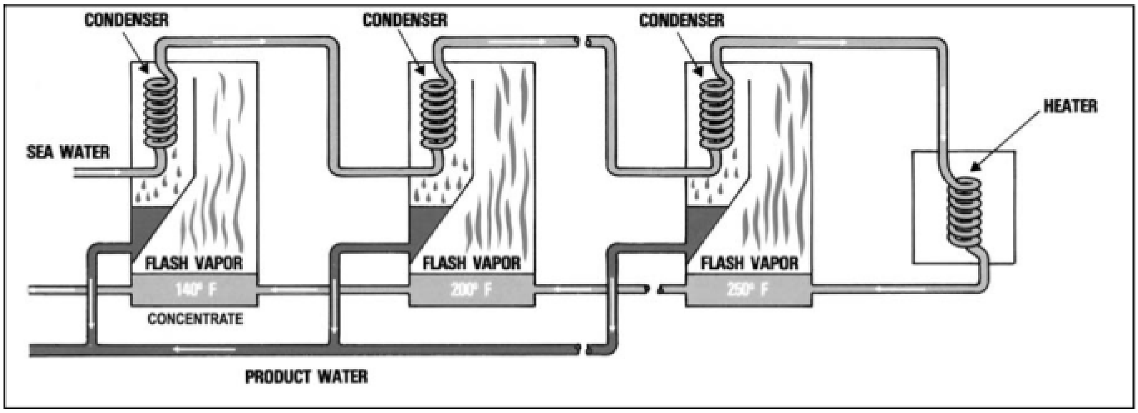


Figure 3.3: Schematic of the MSF distillation system [15].

operating at a lower pressure than the one before. MSF is a relatively mature and robust technology and used around the world mainly for seawater desalination. Figure 3.3 shows a schematic of an MSF system.

3.2.2 Multi Effect Distillation

MED, like MSF, is also a thermally-driven water treatment technology based on distilling the feedwater. In this approach, the fundamental principle is to apply enough energy to cause the feedwater to boil and then supply the additional energy required for the heat of vaporization to convert some of the water to steam [16]. The steam is subsequently condensed to pure water. To make the system more efficient, several stages or "effects" can be used each one at a subsequently lower pressure than the one before allowing boiling to occur at lower temperatures thus requiring minimal to no additional energy. Like MSF, MED is a mature and robust technology used around the world mainly for seawater desalination. Figure 3.4 shows a schematic of the MED system.

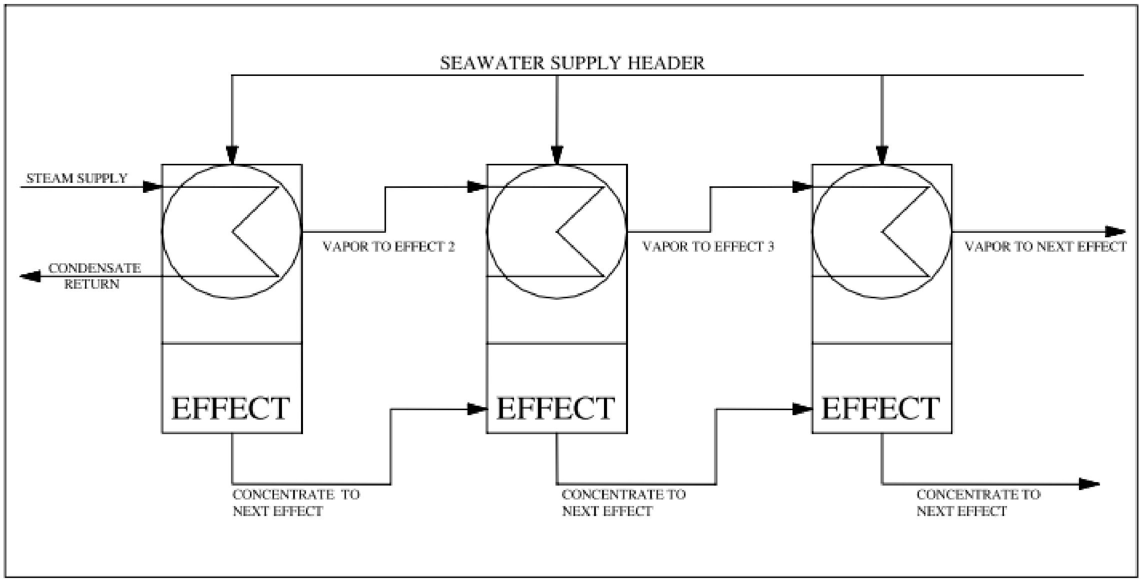


Figure 3.4: Schematic of the MED distillation system [15].

3.2.3 Mechanical Vapor Recompression (MVR)

The details on this technology are based on the NOMAD system engineered and build by Aqua-Pure Ventures Inc. This system was designed to help address some of the specific challenges associated with treating wastewaters from oil and gas production including 1) portability and size of the treatment system, 2) minimizing scale deposition that often occurs with more conventional thermal technologies, 3) the variability in wastewaters produced from oil and gas, and 4) maximizing recovery of product water.

The wastewater treated by this system is first dosed with flocculants to help remove organic matter and suspended solids. Once flocs have formed, the wastewater travels through an inclined separator to remove flocs from the wastewater. Next, the feedwater is heated using a compressor to add enough energy to boil the water. Some of that heat is then reabsorbed from both the distillate and the concentrate

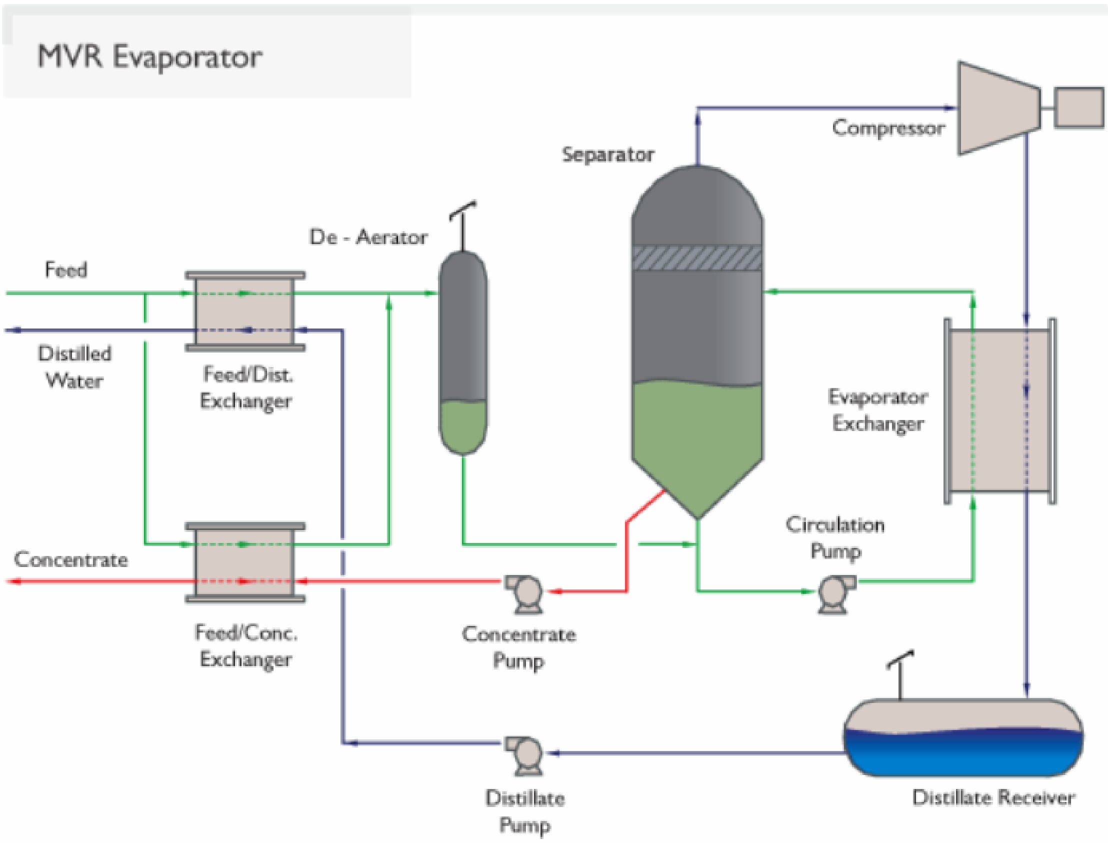


Figure 3.5: Schematic of the MVR distillation system [16].

as these streams pass through heat exchangers. The recovered heat is then reused to heat additional feedwater. Figure 3.5 shows a schematic of the Aqua-Pure MVR Evaporator.

3.2.4 Membrane Separation (MD)

MD is a thermally driven membrane separation technology that can handle high TDS concentrations utilizing low-grade heat producing product water comparable in quality to that of the traditional thermal treatment technologies [40]. The hydrophobic membrane is microporous, allowing pure vapor to separate from an aqueous feed stream through the pores due to surface tension forces. Despite these benefits,

Table 3.1: Energy intensity and recovery rates of the thermal treatment technologies. The values for thermal energy intensity are MMBTU per cubic meter of product water.

Treatment Technology	Thermal Energy Requirements [$MMBTU/m^3$]	Typical Recovery Rate (%)
Multi-stage Flash Distillation (MSF)	0.18—0.28 [15]	10—20 [15]
Multi-Effect Distillation (MED)	0.15—0.28 [15]	20—67 [15]
Mechanical Vapor Recompression (MVR)	0.11 [41]	70—90 [22, 42]
Membrane Distillaton (MD)	0.14 [43]	62—81 [44]

MD might also require more extensive pre-treatment.

3.2.5 Reverse Osmosis (RO)

Another goal of this research is to understand the potential for using solar photovoltaics (PV) and wind turbines to harness renewable electricity for the purpose of on-site wastewater treatment. Since electricity is being used for this part of the analysis, it is best coupled with a treatment technology that requires only electricity and not thermal energy as well. Reverse Osmosis (RO) is currently one of the best options for coupling electricity with wastewater treatment. As such, this analysis looks at coupling renewable electricity with RO.

The main benefit of using RO instead of one of the thermal treatment options is the total energy requirements are significantly lower. Table 3.2 compares the thermal energy requirements, electricity requirements (in both kWh_e and MMBTU of primary

Table 3.2: Energy intensity and recovery rates of the thermal treatment technologies. The energy requirements are given per cubic meter of product water. Additionally, the electricity requirements are reported both in kWh and MMBTU of primary energy.

Treatment Technology	Thermal Energy Requirements $MMBTU/m^3$	Electricity Requirements kWh_e/m^3 ($MMBTU/m^3$)	Typical Recovery Rate (%)
MSF	0.18—0.28 [15]	2.5—5 (0.022—0.044) [45]	10—20 [15]
MED	0.15—0.28 [15]	1.5—2.5 (0.013—0.022) [45]	20—67 [15]
RO	–	4—6 (0.035—0.053) [45]	30—60 [16]

energy), and typical recovery rates of MSF, MED, and RO, revealing that the overall energy requirements of RO are lower than either MED and MSF.

RO is a pressure driven membrane water purification process. Pressure is applied to the feedwater pushing it towards a semi-permeable membrane that allows water through while restricting the flow of many molecules and ions. Thus, the solute becomes more concentrated than the original feedwater while generating pure water. The applied pressure must be high enough to overcome the osmotic pressure of the system. Figure 3.6 shows a schematic of the RO technology. Like MSF and MED, RO is a mature and robust technology for seawater desalination. Some of the drawbacks of RO as compared to the thermal treatment options is that RO often requires more extensive pretreatment, and because it contains a semi-permeable membrane, it is subject to fouling.

3.2.6 Emerging Technologies

As more producers look for options for efficiently and cost-effectively treating their wastewater, new technologies and improvements to existing technologies are

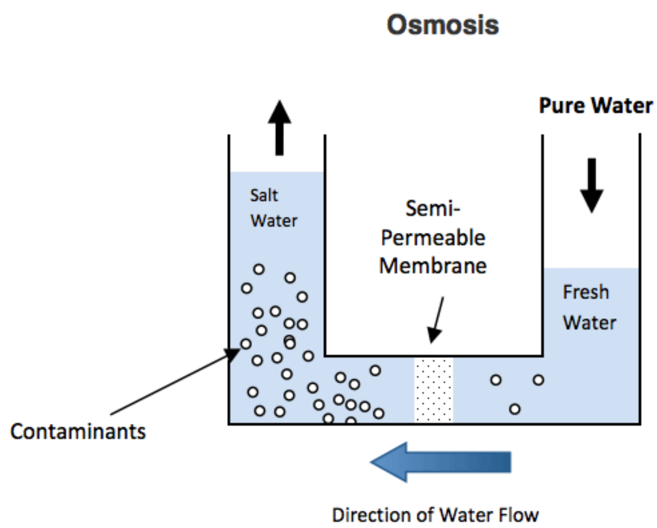


Figure 3.6: Schematic of the RO technology [17].

being made with treatment of oil and gas wastewater being the key application. Forward osmosis is one such emerging technology worth noting for its potential to treat wastewater from hydraulic fracturing utilizing low-grade heat. Additionally, it is often touted for requiring less energy overall than traditional treatment options [46]. This technology is still in the early stages of development for this application and thus was not assessed in this study.

3.3 Flared Natural Gas Volume

Understanding the volume of natural gas that will likely be flared at a well site is important if a producer is interested in harnessing that energy for beneficial use such as for on-site water treatment. Often, a producer will have an expectation for the volume of gas to expect from a well based on gas volumes from adjacent or nearby wells.

There are several scenarios under which a producer might choose to flare natural gas at a well site. In general, regions with minimal to no gas pipeline infrastructure will require flaring of natural gas that is co-produced with oil often including areas of new exploration. Flaring might also occur in regions with gas pipelines if they are already at maximum capacity. Other potential reasons a producer will choose to flare are 1) gas plant shutdowns and 2) maintenance or repair of a compressor, gas line, or well [18].

As mentioned, flare permits are not required in Texas for the first ten days after well completion or re-completion. If a producer needs to flare beyond this time, a permit must be obtained from the RRC. Permit extensions can be requested for up to a total of 180 days. The RRC will often grant the extension for one of the following reasons:

- Producer is awaiting pipeline construction that is expected to be completed by a specific date.
- Producer needs more time for well clean up.
- Producer needs more time to negotiate terms with landowners.

In 2012, the RRC issued 1,963 flaring permits. That number jumped to 3,012 in 2013 [18]. Additionally, as of May 2013 approximately 0.6% of the total amount of gas reported to the RRC was being flared, up from 0.1% in late 2010. Figure 3.7 shows both the statewide gas production and the steady increase in the percentage of total gas reported that is flared over the last several years.

In Texas, producers are required to measure and report the volume of natural gas they flare [18]. Production data, including the reported volume of flared natural gas, is made available to the public through the Railroad Commission of Texas' website. In the specific case of the Permian Basin, the pipeline infrastructure is available

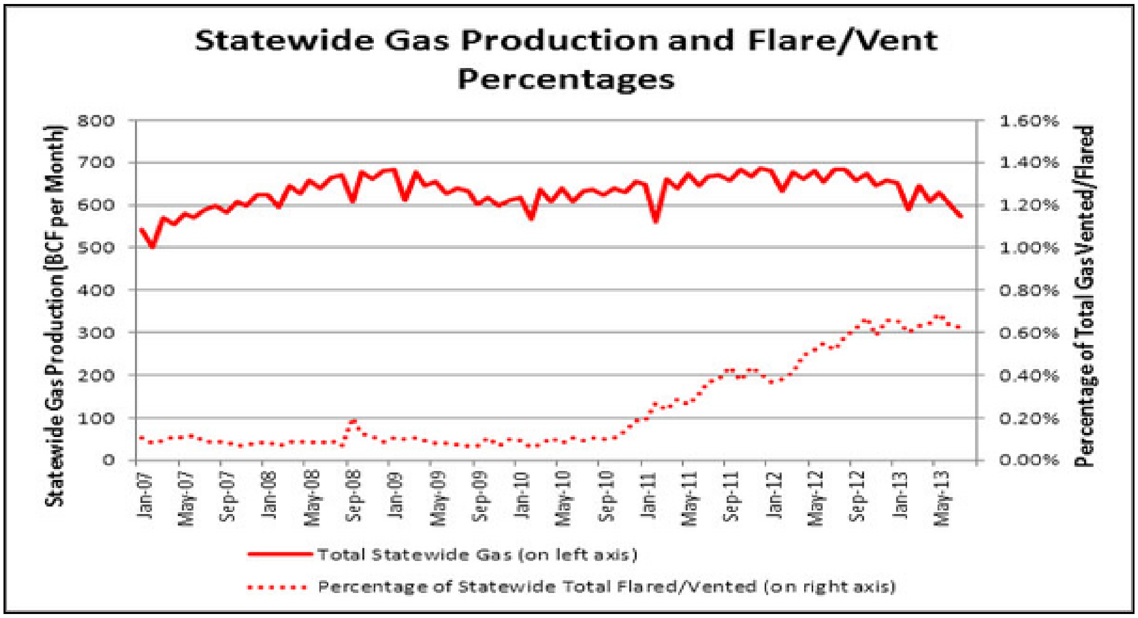


Figure 3.7: Texas gas production and percentage of total gas production that is flared from 2007 through May 2013 [18].

and sufficient to pipe the majority of produced natural gas to market, minimizing flared gas in the region. However, in other regions, flaring is much higher. In 2012, a total of 48 billion cubic feet (BCF) of natural gas was flared in Texas [47].

3.4 Renewable Resources

Some regions heavy in hydraulic fracturing activity also have abundant solar or wind resources. Producers in these regions might consider installing photovoltaic (PV) panels or wind turbines to generate the required electricity from solar and wind energy, respectively, to power wastewater treatment. PV panels are used to convert solar radiation into electricity while wind turbines convert kinetic energy from the wind into electricity.

Implementing renewable resources has some challenges including 1) the cost of installation and maintenance and 2) their inherently intermittent nature. A producer would be required to make a significant capital investment to install the number of photo-voltaic panels or wind turbines to meet the necessary energy requirements of treatment and then potentially incur additional expenses to maintain them. Additionally, both of these resources have diurnal and seasonal variability. For example, solar is only available during the day when the sun is out and inland wind speeds are often higher during the evening and night hours. Intermittency might be less of a concern if a producer has holding tanks or impoundments of sufficient size to pool the generated wastewater and subsequent product water.

3.5 Additional Considerations

In addition to the key technical factors discussed in this chapter, many additional financial and social considerations exist, including the monetary cost associated with implementing on-site treatment and current or future policies and regulations surrounding flaring, water use, and wastewater disposal for shale production. Incorporating associated costs is part of the planned future work and discussed further in the Conclusions chapter of this thesis.

Chapter 4

Flared Gas for On-site Hydraulic Fracturing Wastewater Treatment

4.1 Objectives

The objective for this analysis was to establish an analytical framework to 1) assess technical feasibility for using recovered natural gas for on-site treatment of wastewater, 2) calculate the potential water savings, and 3) determine the energy requirements if such a strategy were implemented. More specifically, the following questions are investigated in this analysis:

1. What is the volume of natural gas required by each of the assessed treatment technologies on a per-well basis to meet the thermal energy requirements for treating the wastewater generated in the first ten days after well completion?

2. What is the volume of product water generated over the first ten days after well completion based on the treatment technology?

3. Using 2012 as a benchmark, what is the theoretical maximum volume of wastewater that could have been treated had all the flared gas in Texas that year been used to power the different treatment technologies?

4.2 Equations and Analysis

The volume of product water, V_{PW}, in cubic meters per completed well is a function of the total cubic meters of wastewater, V_{WW}, the fraction of wastewater that will be treated, F_{treat}, and the recovery rate of the given technology, $F_{recovery}$, as described by Equation 4.1.

$$V_{PW}\left[\frac{m^3}{well}\right] = V_{WW}\left[\frac{m^3}{well}\right] \times F_{treat} \times F_{recovery} \tag{4.1}$$

The thermal energy required per well for treatment of that water in MMBTU is a function of the total cubic meters of product water, V_{PW} and the energy intensity, MMBTU per cubic meter, of the treatment technology, e_{treat} as described by Equation 4.2.

$$E_{treat}\left[\frac{MMBTU}{well}\right] = V_{PW}\left[\frac{m^3}{well}\right] \times e_{treat}\left[\frac{MMBTU}{m^3}\right] \tag{4.2}$$

While the number of potential truck trips saved was not the focus of this study, it could be an added co-benefit of on-site water treatment and reuse. The number of truck trips that are potentially avoided on a subsequent well is related in two ways to the volume of product water generated on-site and used for that well. First, using the product water reduces the number of trucks required to bring in freshwater to the well. Second, it also decreases the number of truck trips required to haul wastewater to a disposal site. This relationship is described in Equation 4.3. A reduction in trucking subsequently reduces interference with local communities, such as that caused by increased traffic, air pollution, and noise pollution.

$$N_{trips}\left[\frac{trips}{well}\right] \propto 2[trips] \times \frac{V_{PW}[\frac{m^3}{well}]}{21[m^3]} \tag{4.3}$$

The relationship described in Equation 4.3 was derived from the assumption that for every approximately 21 cubic meters (or 5,500 gallons, the average capacity of a water truck) of water that can be reused at a nearby well, a producer could potentially save a truck trip hauling freshwater to the site and a truck trip hauling away that volume of wastewater; a total of two truck trips potentially saved. Estimating an accurate value for the truck trips saved is more complicated than the relationship described in Equation 3 given the various logistical challenges associated with ensuring a sufficient amount of water is available at the appropriate time for each well fracture. Despite the complexity, it is generally agreed that treating and reusing the water on-site will either reduce the overall number of trucks required to haul water to and from the well site or will reduce the distance those trucks have to travel and thus reduce truck traffic in the region as well [48].

Given that 1) a permit is not required, 2) wastewater TDS concentrations are still relatively low, and 3) wastewater flow rates are at their highest, the first ten days after well completion is an ideal time for using natural gas for the purposes of on-site treatment (shown in Figure 4.1). To treat the wastewater in real-time using the on-site gas, the volume of natural gas that would be flared per unit time should be determined and compared to the energy requirements of the potential treatment options. In this study, we assume that the volume of flared natural gas is constant over the first ten days after well completion. Based on the 2012 values for the total wells completed, the number of flare permits issued, and the total volume of flared natural gas from oil and gas production in Texas, a rough estimate for the volume of flared gas is approximately 9,600 m^3/well/day. This value has uncertainty in that it underestimates the volume of flared gas in regions where flaring is abundant and overestimates in areas where little to no flaring is occurring. Despite this limitation, this estimate provides a general sense for how much natural gas is being flared per day, on average, per well in Texas over the first ten days of production.

For the purpose of this study, the necessary volume of natural gas was cal-

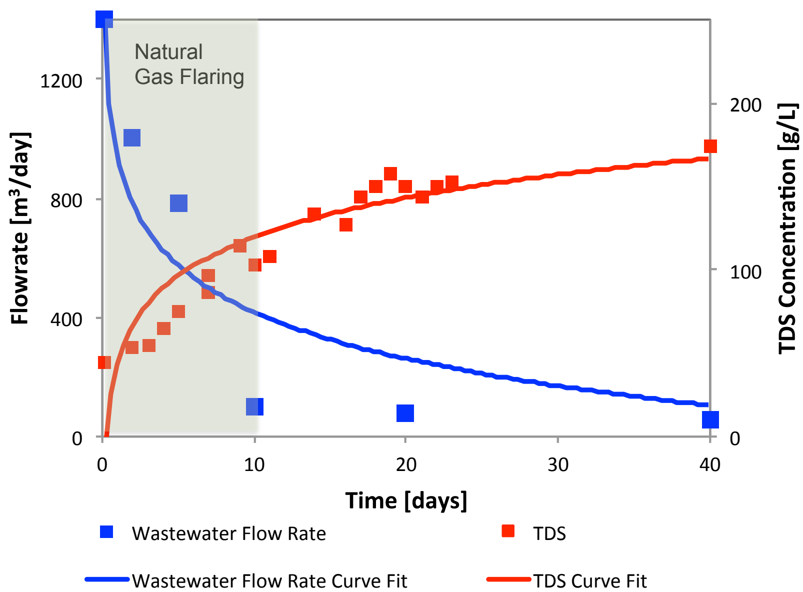


Figure 4.1: This figure shows data and the logarithmic fitted curves, for TDS concentration and hydraulic fracturing wastewater up to 40 days after the well is drilled [14]. In general, flow rates from shale production sites generally decrease with time (starting in days after initial production), while TDS levels increase over time. Exact values vary from well to well and from field to field but the overall trends are nominally similar. At the same time, gas is often flared in Texas for the first ten days after well completion. That means the first ten days after completion are a sensible time for using gas to treat high volumes of wastewater that have relatively low TDS concentrations.

culated per cubic meter of product water for the thermal energy requirements for the different treatment technologies, benchmarking these values against one another. Equation 4.4 calculates the volume of natural gas, in cubic meters per well, required for treating the wastewater produced in the first ten days after well completion based on treatment technology. There is approximately 0.036 MMBTU of energy in one cubic meter of natural gas.

$$V_{natgas}\left[\frac{m^3}{well}\right] = \frac{e_{treat}\left[\frac{MMBTU}{m^3\,of\,PW}\right] \times V_{PW}\left[\frac{m^3}{well}\right]}{0.036\left[\frac{MMBTU}{m^3\,of\,natural\,gas}\right]} \tag{4.4}$$

An average of almost 19,000 cubic meters per well are used for the hydraulic fracturing process on horizontal wells in the Permian Basin with an average of 35% of the volume of the initially injected fluid returning to the surface within approximately the first two months [2, 42]. Based on Figure 3.2, approximately 7,500 cubic meters of wastewater return to the surface within the first ten days after well completion. Given this volume of wastewater, the energy required for treatment, the corresponding volume of natural gas required, and the volume of product water were calculated on a per-well basis. It was determined that the thermal energy required per well for wastewater treatment over the first ten days is 140–820 MMBTU and would yield 750–6,800 cubic meters of product water depending on the treatment technology.

In total, Texas flared 48 billion cubic feet of natural gas and completed 15,041 new oil and gas wells in 2012 [47,49]. Based on treatment technologies assessed in this study, this volume of flared gas is enough to cover the thermal energy requirements to treat 0.5 to 2.7 billion cubic meters of wastewater, which would yield 180 to 540 million cubic meters of product water. That is enough water to meet the needs for hydraulically fracturing 9,400 to 28,000 wells. That is also approximately 3 to 9% of the state's annual water demand for municipal purposes or 1 to 2.4% of total

Table 4.1: Summary of the energy required, the corresponding volume of natural gas, and volume of product water per well if the wastewater generated in the first ten days after well completion is treated using one of the following treatment technologies assessed.

Treatment Technology	Thermal Energy for Treatment Required [MMBTU/well]	Volume of Natural Gas [m^3/well]	Product Water [m^3/well]
MSF	140—410	3,800—11,400	750—1500
MED	220—720	6,000—20,000	1,500—5,000
MVR	580—740	16,000—20,500	5,300—6,800
MD	630—820	17,400—22,700	4,700—6,100

Texas statewide water demand for all purposes in 2012 [1]. Thus, a strategy of treating wastewater from hydraulically fractured shale production sites with energy from flared gas, thereby allowing the avoidance of a preponderance of wastewater injection, could materially increase total statewide water supply.

Table 4.2: A summary of the potential total volume of wastewater that could be treated and resulting product water if the energy from flared natural gas in Texas in 2012 was harnessed for hydraulic fracturing wastewater treatment.

Treatment Technology	Potential volume of wastewater that could be treated [million m^3]	Potential volume of product water [million m^3]
MSF	900—2,700	180—270
MED	510—1,700	180—540
MVR	500—640	450
MD	450—590	360

Chapter 5

Renewable Electricity for On-site Hydraulic Fracturing Wastewater Treatment

5.1 Objectives

In addition to flared gas, the Permian Basin has significant solar and wind energy resources that can be harnessed for the purpose of supplying electricity for on-site water treatment. The objective for this analysis was to establish an analytical framework to investigate the following:

1. Assess technical feasibility for using solar and wind renewable resources for on-site treatment of wastewater. That is, what is the amount of solar or wind power required to meet the energy demands for the different treatment technologies on a per well basis? How many PV panels or wind turbines would be required to meet this demand?

2. Calculate the potential water savings.

3. What is the overall potential avoided fossil fuel consumption from water acquisition through wastewater disposal if such a strategy were implemented?

To answer these research questions, the energy consumed for water management upstream and downstream of a hydraulic fracturing operation was calculated for two scenarios: 1) current water management practices in the region and 2) a regime where on-site wastewater treatment using renewable resources is implemented.

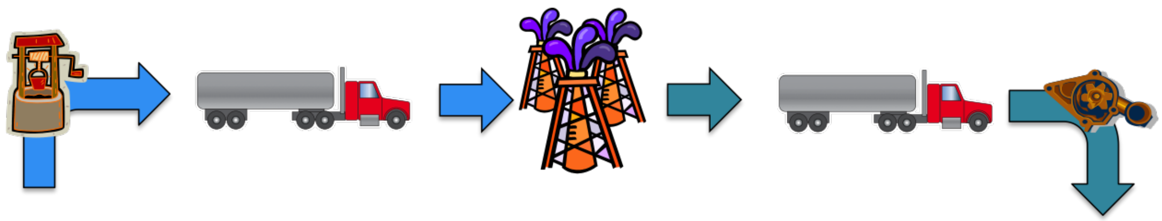


Figure 5.1: This figure shows the current water management strategy for hydraulic fracturing operations in the Permian Basin where the majority of the water is pumped from local groundwater, trucked or piped to the well site, used for fracking, and then trucked or piped to a disposal well. The schematic shows water being trucked to and from the well site instead of piped as this would be the worst case scenario from an energy intensity standpoint.

5.2 Boundaries and Equations

5.2.1 Current Paradigm

While water is scarce in the Permian Basin, and many producers are actively exploring additional water resources for their oil and gas production, the vast majority of the water is still currently pumped from nearby groundwater wells, and most of the generated wastewater is disposed via deep well injection. Figure 5.1 shows a schematic of the current water management strategy in the region.

The boundaries for this assessment were set to the energy required for pumping groundwater, $E1_{pump,W}$, trucking that water to the well site, $E1_{truck,in}$, and trucking from the well site to the disposal site, $E1_{truck,out}$ as shown in Equation 5.1 and per Figure 5.2. The energy consumed for the hydraulic fracturing operation was not calculated because it was assumed to be the same in both the current paradigm and the proposed strategy. Additionally, the energy for deep well injection (DWI) was not included. There are several forces at play in DWI including gravity, the pump, friction from the pipes, and resistance from the formation into which the wastewater is being injected. Within each of these forces, there are a number of

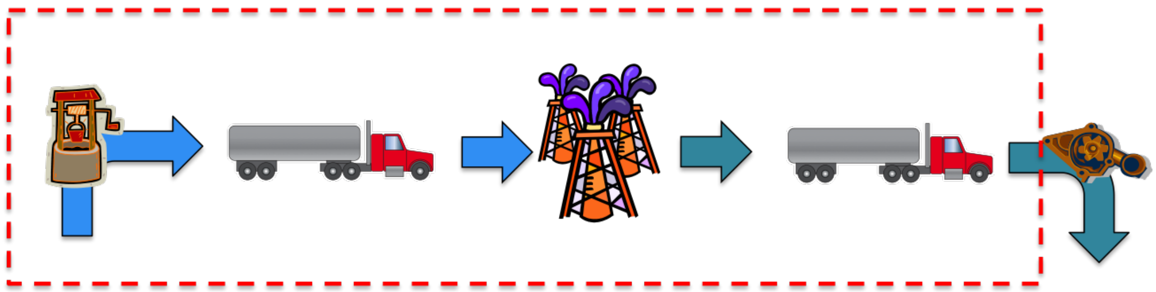


Figure 5.2: This figure shows the system boundaries for the current paradigm in this analysis. Included in the system boundaries are the energy for 1) pumping groundwater, 2) trucking the water to the well site, and 3) trucking the wastewater from the well site to a disposal well. Not included in the system boundaries are 1) the energy for hydraulic fracturing as this value is assumed to be the same in the current paradigm and proposed strategy and 2) the energy for DWI.

variables that would need to be determined to calculate the energy for disposal via DWI of which several are specific to the disposal site and fairly difficult to obtain and potentially highly variable. As such, the energy for DWI was not included within the system boundaries. Equation 5.1 calculates the total primary energy required through normalizing electricity and diesel fuel in units of MMBTU by multiplying the electricity required for pumping by the average electrical U.S. heat rate conversion factor [4].

$$E1_{tot}[MMBTU] = E1_{pump,W} \times ec_{BTU} + E1_{truck,in} + E1_{truck,out} \tag{5.1}$$

The energy to pump groundwater is a function of the volume of groundwater to be pumped, V_W, the density of the water, ρ_W, the height over which the water will be elevated, H_W, gravity, g, and the efficiency of the pump, η_{pump}, as described in Equation 5.2.

$$E1_{pump,W}[MWh] = V_W[m^3] \times \rho_W \left[\frac{kg}{m^3}\right] \times H_W[m]$$
$$\times g \left[\frac{m}{s^2}\right] \times \frac{1}{\eta_{pump}} \times \left[\frac{1\,MWh}{3.6 \times 10^9\,Joules}\right] \tag{5.2}$$

Equation 5.3 shows the conversion from the calculated amount of electricity required for pumping to the equivalent amount of primary energy.

$$E1_{pump,W}[MMBTU] = E1_{pump,W}[MWh] \times ec_{BTU} \left[\frac{MMBTU}{kWh}\right] \times \left[\frac{1000\,kWh}{1\,MWh}\right] \tag{5.3}$$

The energy required for trucking the water from the groundwater well to the well site depends on the volume of water being trucked, $V_{W,in}$, the distance the truck must travel from groundwater pump site to the well site, D_{in}, the energy density of the fuel (in this case diesel) used, ω_{diesel}, the water storage capacity of the truck, C_{truck}, and the fuel efficiency of the truck (i.e. average miles per gallon), FE_{truck} as described in Equation 5.4.

$$E1_{truck,in}[MMBTU] = V_{W,in}[m^3] \times D_{truck,in} \left[\frac{miles}{truck}\right] \times \omega_{diesel} \left[\frac{BTU}{gal}\right]$$
$$\times \frac{1}{C_{truck}} \left[\frac{truck}{m^3}\right] \times \frac{1}{FE_{truck}} \left[\frac{gal}{miles}\right] \times \left[\frac{1\,MMBTU}{10^6\,BTU}\right] \tag{5.4}$$

The required energy for trucking out the wastewater is similar to Equation 5.4, however, the distance traveled to the disposal well will likely differ and is given by Equation 5.5.

$$E1_{truck,in}[MMBTU] = V_{W,out}[m^3] \times D_{truck,out}\left[\frac{miles}{truck}\right] \times \omega_{diesel}\left[\frac{BTU}{gal}\right]$$
$$\times \frac{1}{C_{truck}}\left[\frac{truck}{m^3}\right] \times \frac{1}{FE_{truck}}\left[\frac{gal}{miles}\right] \times \left[\frac{1\,MMBTU}{10^6\,BTU}\right] \quad (5.5)$$

5.2.2 Proposed Strategy

In the proposed strategy, on-site treatment using RO is introduced powered by either electricity generated from solar or wind energy to treat a portion of the wastewater for subsequent reuse at a nearby well. Figure 5.3 shows a schematic of the proposed strategy and includes the system boundaries. The total energy for this scenario has the same components as the current paradigm but also includes the energy for treatment, $E2_{treat}$, per Equation 5.6. The volume of wastewater that would be treated using RO was kept at 7500 m^3, the approximate amount of wastewater that returns in the first 10 days post well completion (per Figure 3.2), and the same value used in Chapter 4. This value was chosen to take advantage of the relatively low TDS concentration in the wastewater early on after well completion.

$$E2_{tot} = E2_{pump,W} + E2_{truck,in} + E2_{truck,out} + E2_{TRMT,RO} \quad (5.6)$$

Equation 5.7 calculates the electricity required to pump freshwater in the proposed strategy. Equation 5.8 shows the conversion from the calculated amount of electricity required for pumping to the equivalent amount of primary energy.

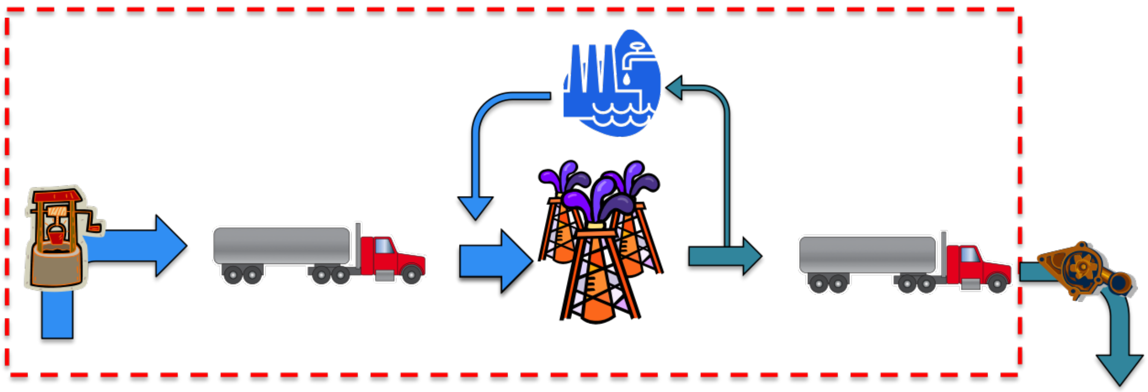


Figure 5.3: This figure shows the system boundaries in the proposed strategy. Included in the system boundaries are the energy for 1) pumping groundwater, 2) trucking the water to the well site, 3) trucking the wastewater from the well site to a disposal well, and 4) the energy required to treat a portion of the wastewater for subsequent reuse at a nearby well. The volume of freshwater required on the subsequent well will be reduced as a result of treating and reusing part of the wastewater and thus reducing the energy for pumping and trucking freshwater. Not included in the system boundaries are 1) the energy for hydraulic fracturing as this value is assumed to be the same in the current paradigm and proposed strategy and 2) the energy for DWI.

$$E2_{pump,W}[MWh] = (V_W - V_{PW})[m^3] \times \rho_W \left[\frac{kg}{m^3}\right] \times H_W[m] \times g\left[\frac{m}{s^2}\right] \times \frac{1}{\eta_{pump}} \times \left[\frac{1\,MWh}{3.6 \times 10^9\,Joules}\right] \tag{5.7}$$

$$E2_{pump,W}[MMBTU] = E2_{pump,W}[MWh] \times ec_{BTU} \left[\frac{MMBTU}{kWh}\right] \times \left[\frac{1000\,kWh}{1\,MWh}\right] \tag{5.8}$$

The energy required for trucking water in the proposed strategy differs to that in the current paradigm in that less freshwater will be required since some of the wastewater will be treated on-site and be reused. As such, the volume of freshwater that would be trucked in depends on the volume of water required to hydraulically fracture a well minus the amount of product water generated, V_{PW}, from on-site treatment as shown in equation 5.9. Similarly, the volume of wastewater that will need to be trucked to a disposal site will be reduced by the volume of product water generated from on-site treatment as shown in Equation 5.10.

$$E2_{truck,in}[MMBTU] = (V_{W,in} - V_{PW})[m^3] \times D_{truck,in}\left[\frac{miles}{truck}\right] \times \omega_{diesel}\left[\frac{BTU}{gal}\right] \times \frac{1}{C_{truck}}\left[\frac{truck}{m^3}\right] \times \frac{1}{FE_{truck}}\left[\frac{gal}{miles}\right] \times \left[\frac{1\,MMBTU}{10^6\,BTU}\right] \tag{5.9}$$

$$E2_{truck,out}[MMBTU] = (V_{W,out} - V_{PW})[m^3] \times D_{truck,out}\left[\frac{miles}{truck}\right]$$

$$\times \omega_{diesel}\left[\frac{BTU}{gal}\right] \times \frac{1}{C_{truck}}\left[\frac{truck}{m^3}\right] \tag{5.10}$$

$$\times \frac{1}{FE_{truck}}\left[\frac{gal}{miles}\right] \times \left[\frac{1\,MMBTU}{10^6\,BTU}\right]$$

The electricity required for treatment using RO, $E2_{TRMT,RO}$, is a function of the product water volume, V_{PW}, and the energy intensity of RO, $e_{TRMT,RO}$ as described in Equation 5.11. Equation 5.12 shows the conversion from the calculated amount of electricity required for treatment to the equivalent amount of primary energy.

$$E2_{TRMT,RO}[MWh] = V_{PW}[m^3] \times e_{TRMT,RO}\left[\frac{MWh}{m^3}\right] \tag{5.11}$$

$$E2_{TRMT,RO}[MMBTU] = E2_{TRMT,RO}[MWh] \times ec_{BTU}\left[\frac{MMBTU}{kWh}\right] \times \left[\frac{1000\,kWh}{1\,MWh}\right] \tag{5.12}$$

5.3 Analysis

5.3.1 Energy Requirements of Current Paradigm vs. Proposed Strategy

Using the equations described in previous sections of this chapter along with the parameters defined and summarized in Table 5.2, the total energy for both the current paradigm and the proposed strategy were calculated and are summarized in Table 5.1. As mentioned previously, it was assumed that approximately 7,500 m^3

Table 5.1: A summary of the energy requirements for pumping freshwater, trucking that water to the well site, trucking the wastewater to a disposal well, and treatment using RO. In order to compare the overall energy requirements, the electricity requirements were also converted to MMBTU of primary energy using the average U.S. heat rate [4].

	Energy for pumping freshwater MMBTU (MWh)	Energy for trucking water to well site MMBTU	Energy for trucking water to disposal well MMBTU	Energy for RO MMBTU (MWh)	Total Energy MMBTU
Current Paradigm	15–75 (1.7–8.5)	348–921	116–553	–	480–1549
Proposed Strategy	13–59 (1.5–6.7)	302–722	101–493	80–238 (9–27)	496–1512

of wastewater per well would be treated via RO generating between 2,250 and 4,500 m^3 of product water (based on the typical recovery rates for RO as described in Table 3.2), a potential water savings of approximately 11 to 26% on the subsequent well. As Table 5.1 reveals, the calculated total energy of the proposed strategy is approximately equivalent to the energy for the current paradigm. However, it should be noted that the energy for treatment would be supplied entirely from renewable electricity. If the energy required for treatment is removed from the overall energy requirements in proposed strategy, there is an overall energy savings of approximately 16%.

5.3.2 Renewable Energy Requirements for Treatment

To determine the solar power necessary for treating the desired volume of wastewater, the peak PV power, P_a, was calculated. Peak PV power is a function

Table 5.2: This table summarizes the variables and parameters required in Equations 5.1 through 5.12.

Variable	Description	Min	Max	Units	Source
$V_{W,in}$	volume of water to be pumped and trucked to well site	17,000	20,800	m^3	[2]
$V_{W,out}$	volume of wastewater to be trucked to disposal site	17,000	41,600	m^3	[2]
$\rho_{W,in}$	density of freshwater	1,000	1,000	kg/m^3	constant
$\rho_{W,out}$	density of produced water	1025	1025	kg/m^3	constant
H_W	difference in elevation between pump and groundwater aquifer	15	90	m	[50]
g	gravimetric constant	9.8	8.8	m/s^2	constant
η_{pump}	fractional efficiency of water pump	0.4	0.6	–	[51]
$D_{truck,in}$	distance traveled from groundwater aquifer to well site	15	50	$mi/truck$	[51]
$D_{truck,out}$	distance traveled from well site to disposal site	5	15	$mi/truck$	[51]
ω_{diesel}	primary energy density of diesel fuel	129,000	129,000	BTU/gal	constant
C_{truck}	water storage capacity of water truck	18.9	20.8	$m^3/truck$	[51]
FE_{truck}	diesel fuel efficiency of water truck	5	7	mi/gal	[51]
ec_{BTU}	electrical conversion factor from kWh to MMBTU based on average U.S. heat rate	0.00883	0.00883	$MMBTU/kWh$	[4]

of the energy for treatment, $E2_{TRMT,RO}$, solar energy (irradiation), I, a temperature correction coefficient, T_c, the pollution coefficient, P_c, and an efficiency factor of the PV system (due to inefficiencies in batteries, inverter, etc.), E_{PV}, as described in Equation 5.13 [52]. The temperature correction coefficient, T_c, was calculated based on the ambient temperature, T_a and module temperature, T_m as shown in Equation 5.14 [52]. Once the peak PV power is determined, the number of panels required can be calculated and is a function of peak PV power, P_a and the power rating for the panel, P_{panel} as shown in Equation 5.15. Additionally, it was assumed that there is a battery bank that can store enough solar energy allowing for two days of system autonomy. To meet the peak PV power, it was determined that between 1,161 and 3,728 250W PV panels would be required for RO treatment. Table 5.3 summarizes the required energy for RO, peak PV power, and the number of panels that would be required and Table 5.4 defines and summarizes the parameters in Equations 5.13 through 5.15.

$$P_a[kW] = \frac{E2_{TRMT,RO}}{IT_cP_cE_{PV}} \tag{5.13}$$

$$T_c = 1 - 0.005(T_m - 20) \tag{5.14}$$

$$N_{PV} = \frac{P_a}{P_{panel}} \tag{5.15}$$

The total wind power, P_w that would be required is a function of the energy required for treatment, $E2_{TRMT,RO}$, the total time for treatment, t_{TRMT} and the capacity factor of the wind turbine, CF as shown in Equation 5.16. The energy for treatment using RO per day was previously determined to be between 900 to 2,700

Table 5.3: This table summarizes the required energy for RO, peak PV power, and the number of panels that would required for treating a portion of the wastewater on-site.

Variable	Description	Low	High	Units
$E2_{TRMT,RO}$	energy required for RO treatment	900	2,700	kWh/day
P_a	peak PV power	932	290	kW
N_{PV}	# of PV panels to meet peak PV power	1,161	3,728	panels

Table 5.4: This table defines and summarizes the parameters in Equations 5.13 through 5.15

Variable	Description	January	June	Units	Source
T_a	ambient temperature	6.6	26.9	$°C$	[53, 54]
T_m	module temperature	36.6	56.9	$°C$	[52]
P_c	atmospheric dirt coefficient	0.9	0.9	–	[52]
I	average tilt solar radiation	5.4	6.5	$kWh/m^2/day$	[10]
T_c	temperature correction factor	0.92	0.82	–	calculated

kWh (summarized in Table 5.3). Additionally, it was assumed that there is a battery bank that can store enough wind energy for two days of system autonomy. Using a capacity factor of 0.35 for the wind turbine and assuming the treatment facility runs 24 hours a day, the total wind power that would be required is between 107 and 322 kW [55]. This power requirement could be met by at least four relatively small 100 kW wind turbines.

$$Pw[kW] = \frac{E2_{TRMT,RO}}{t_{TRMT} \times CF} \tag{5.16}$$

Chapter 6

Conclusions

6.1 Summary of Main Findings

6.1.1 Flared Gas Main Findings

By using the energy requirements of several thermal treatment options and wastewater characteristics it was determined that the thermal energy required per well for wastewater treatment over the first ten days is 140-820 MMBTU and would yield 750-6,800 cubic meters of product water. Additionally, given the volume of natural gas flared in Texas in 2012, the theoretical maximum volume of product water that could have been generated was 180–540 million cubic meters, approximately 3–9% of the state's annual water demand for municipal purposes and 1–2.4% of total Texas statewade water demand for all purposes [1].

6.1.2 Renewable Electricity Main Findings

In this analysis, the energy requirements for water management upstream and downstream of a well for both the current paradigm and a proposed strategy (where a portion of the wastewater is treated on-site using renewable electricity and reused on a subsequent well) were calculated and compared. Through performing this analysis, it was determined that the proposed strategy could provide water savings of between 11 and 26%, which could be especially significant in drought-stricken and water-stressed regions. Additionally, this approach could displace approximately 16% of the fossil fuel energy requirements for pumping freshwater, trucking that water to the well site, and trucking wastewater to a disposal well. To power wastewater treatment from solar or wind, it was calculated that 1,161 to 3,728 250W PV panels, or at least four 100 kW wind turbines, respectively, would be required.

6.2 Recommendations

The rules and regulations surrounding hydraulic fracturing are likely to become more stringent in the near future as more is learned about the variety of impacts and challenges the practice presents to the surrounding environment and communities and as activity continues to increase across the country. Some of the challenges are already fairly well understood and many producers are actively working to mitigate impacts where possible. The work described here investigates two ways of reducing the water use, generated wastewater, flared natural gas without application, and truck-miles required for fracking.

Based on the results of this work, regions that have sufficient volumes of natural gas that is often flared due to little or no gas pipeline infrastructure could consider on-site thermal treatment technologies for generating product water. This approach is especially pertinent for producers in regions that are compounded by water scarcity (where the product water could be used on a subsequent well) or have minimal wastewater disposal options. In areas where there is abundant solar and wind energy resources and flaring is not as pervasive, producers could consider installing either PV panels or wind turbines to meet the requirements for powering wastewater treatment using RO.

6.3 Future Work

Obtaining more granular information on the location and availability of the flared natural gas, regional wastewater flow rates, and wastewater quality could augment this framework to identify suitable treatment options and corresponding water recovery rates. Possible future work would include refining this framework by shale region to obtain more accurate values for the volume of wastewater that could be treated. Additionally, understanding and incorporating the cost trade-offs of implementing water treatment would be important to the producers. Future work should also include an assessment of the energy requirements, water savings, and costs associated with more of the emerging treatment technologies in this space. Lastly, an understanding of the temporal aspects such as how much natural gas is being co-produced and available compared to the wastewater flow rates. Do these variables align? If not, what size holding tanks would be needed to store natural gas and wastewater?

Currently, much of this information is either proprietary or difficult to obtain. However, given the rapid pace of the industry and growing desire for on-site wastewater treatment from both producers and the public, opportunities for timely and relevant analysis will potentially emerge, as these data become more available.

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Vita

Yael was born in Haifa, Israel and raised in Palo Alto, California. She received a Bachelor of Science in Bioengineering from the University of California, Berkeley in 2004. She spent the next seven years working at Genentech, one of the world's leading biotech companies, developing and optimizing manufacturing processes to bring medicines to patients with unmet medical needs such as auto-immune diseases, cancer, and Alzheimer's disease. The biotech industry's massive dependence on clean water drove her curiosity about the overall world water crisis. Her interest quickly developed into a passion and led her to pursue a graduate degree at The University of Texas at Austin.

Permanent address: 502 E. 41st St.
Austin, Texas 78751

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