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LETTER

Flared natural gas-based onsite atmospheric water harvesting (AWH) for oilfield operations

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Abstract

Natural gas worth tens of billions of dollars is flared annually, which leads to resource waste and environmental issues. This work introduces and analyzes a novel concept for flared gas utilization, wherein the gas that would have been flared is instead used to condense atmospheric moisture. Natural gas, which is currently being flared, can alternatively power refrigeration systems to generate the cooling capacity for large scale atmospheric water harvesting (AWH). This approach solves two pressing issues faced by the oil–gas industry, namely gas flaring, and sourcing water for oilfield operations like hydraulic fracturing, drilling and water flooding. Multiple technical pathways to harvest atmospheric moisture by using the energy of natural gas are analyzed. A modeling framework is developed to quantify the dependence of water harvest rates on flared gas volumes and ambient weather. Flaring patterns in the Eagle Ford Shale in Texas and the Bakken Shale in North Dakota are analyzed to quantify the benefits of AWH. Overall, the gas currently flared annually in Texas and North Dakota can harvest enough water to meet 11% and 65% of the water consumption in the Eagle Ford and the Bakken, respectively. Daily harvests of upto 30 000 and 18 000 gallons water can be achieved using the gas currently flared per well in Texas and North Dakota, respectively. In fifty Bakken sites, the water required for fracturing or drilling a new well can be met via onsite flared gas-based AWH in only 3 weeks, and 3 days, respectively. The benefits of this concept are quantified for the Eagle Ford and Bakken Shales. Assessments of the global potential of this concept are presented using data from countries with high flaring activity. It is seen that this waste-to-value conversion concept offers significant economic benefits while addressing critical environmental issues pertaining to oil–gas production.

1. Introduction

Associated natural gas (gas co-produced with oil) is flared in many regions which lack adequate gas gathering and transportation infrastructure. Flaring is practiced when the rate of return on capital and operating expenses to collect and utilize this gas is negative. Investment on gas collection and handling infrastructure (pipelines, compressors, processing facilities) is not justified in many oil–gas producing regions. Importantly, many new fields like the Bakken Shale are predominantly oil plays, where gas has a lower economic value. Furthermore, gas production from hydraulically fractured oil wells declines rapidly, which makes infrastructure setup challenging. All these factors result in unfavorable economics for the capture and utilization of unwanted natural gas, leaving flaring as the preferred option, when permitted.

Estimates by the EIA [1] and the World Bank [2] show that 5 trillion cubic feet of natural gas, which is 4% of total production, was flared worldwide in 2011. *Natural gas worth* 55 *billion USD was flared worldwide* and gas worth 2.3 billion USD was flared in the US in 2011. These estimates are based on US residential gas prices [1]. The use of wellhead prices reduces the value of the gas flared worldwide to 20 billion USD. Historically, regions [2] with significant flaring have been

Russia, Middle East, West Africa and North Africa. The US has recently become the 5th largest flaring country [2] due to the spike in flaring from hydraulically fractured oil wells. The volume of gas flared in the US increased by 60% between 2009 and 2013 [1]. The fraction of gas flared to gas produced increased [1] from 0.7% in 2009 to 1% in 2013. Locally, the flaring percentages can be significantly higher. The two states responsible for the surge in US flaring are Texas and North Dakota, which account [1] for 30% and 40% of total US flaring, respectively.

Flaring in Texas went up by 117% in just two years from 2011 to 2013 [1]. The major contributor to the increased flaring is the Eagle Ford Shale in south Texas. Eagle Ford accounts for 54% [3] of the flaring in Texas despite having only 3.2% of the state's wells. Recent development of the Eagle Ford has resulted in a 400% increase [4] in flaring from 2009 to 2012. This surge in flaring is also evident from the fact that more than 3000 flaring permits [3] were issued in 2013, compared to 107 permits in 2008. Within the Eagle Ford itself, oil wells account for 87% of total flaring [3]. It is important to note that that flaring values are often underreported since Texas allows reporting exemptions [3, 5] for gas which cannot be easily measured after well completion. More recent estimates [6] show that on average, 340 MCFD (MCFD: thousand cubic feet per day) of gas is flared per well from newly completed wells in Texas.

Up to a third [3] of the gas produced in the Bakken Shale in North Dakota is flared; about 1 billion USD worth of gas was flared in 2013. Certain producers in the Bakken flare up to three quarters of the gas produced [3, 7]. Similar to the Eagle Ford, oil wells account for an overwhelming majority (99%) of flaring [3]. Fifty sites [8] in North Dakota flare more than 1200 MCFD and more than 275 sites flare more than 300 MCFD. It should be noted that flaring volumes are high after a well is completed, but decline rapidly [9] in a few months. The average flaring rate [3] per new well in the first three months of production in the Bakken Shale is 195 MCFD.

Significant flaring is practiced [1] in other oil producing US regions including New Mexico, Wyoming, Gulf of Mexico, Alaska and Montana. Unfavorable economics and inadequate regulation have hindered efforts to reduce flaring. As an illustration, producers in Texas do not pay royalties or taxes on flared gas [3]. There are no flaring restrictions in North Dakota in the first year, when most of the flaring [10] is typically conducted. Recent regulations [10] require producers to have gas capture plans for new fields. However, it is unclear if these regulations will be effective in reducing flaring, since 54% of flaring in North Dakota [11] is from wells already connected to gas gathering infrastructure. In the absence of economic alternatives or regulation, flaring would be the preferred option for the thousands of wells that have been identified for future drilling. Additionally, there exist 72 000 unconventional production wells [12] in the US, which could be flared when they are refractured. Flaring volumes are much higher outside the US [2], but obtaining accurate data is difficult due to inadequate reporting. Overall, it is clear that flaring is a significant waste of global resources and contributes to environmental issues like air, thermal and light pollution.

2. Water challenges for the oil–gas industry

Water procurement for oilfield operations is a significant challenge faced by producers. The water requirements of the industry have increased significantly with the advent of hydraulic fracturing. Hydraulic fracturing of horizontal oil and gas wells requires 6 to 7 times more water than that used in conventional vertical wells [13]. The water use per well [14–17] in the US (based on data from 40 000 wells on FracFocus.org) ranges from 1 to 5 million gallons with an average [14] of 2.5 million gallons/well. It should be noted that other oilfield operations also require water. Drilling and sand mining [15] require 150 000–300 000 gallons per well. While the overall water consumption for oil–gas production is a fraction [14] of the water draws for agriculture, power generation and municipal consumption, water sourcing still presents formidable challenges. A lot of hydraulic fracturing activity coincides with regions having acute water shortages. In 2014 [14], 48% of US wells were in extreme water stress regions, with 80% of available water (surface and ground) already allocated. Additionally, oil producing states like Texas, New Mexico, Colorado and California expect added stress on limited water supplies from projected population increases [18].

The Eagle Ford Shale in Texas can be considered as ground zero for water issues, since it is located in a very dry part of Texas, and hydraulic fracturing operations consume 4.5 million gallons/well [14], which is much higher than the national average. Ninety-eight percent of Eagle Ford wells are located in either medium or extreme water stress areas. Twenty-eight percent of these wells lie in extreme water stress areas [14]. Groundwater from the Carrizo–Wilcox aquifer is currently being used [14], but reserves are being rapidly depleted.

Drilling and hydraulic fracturing of up to 40 000 new wells [14] has been planned for the Bakken Shale. Despite a Bakken well needing a moderate 2.2 million gallons [14] of water (for hydraulic fracturing), there are significant local challenges to water procurement. Limited freshwater depots translate to long trucking distances and transportation costs approaching $5/barrel of water [19, 20]. Lack of access points for surface water extraction, seasonal flow variations of surface water and permitting delays for groundwater are other barriers to procurement [21]. Obtaining

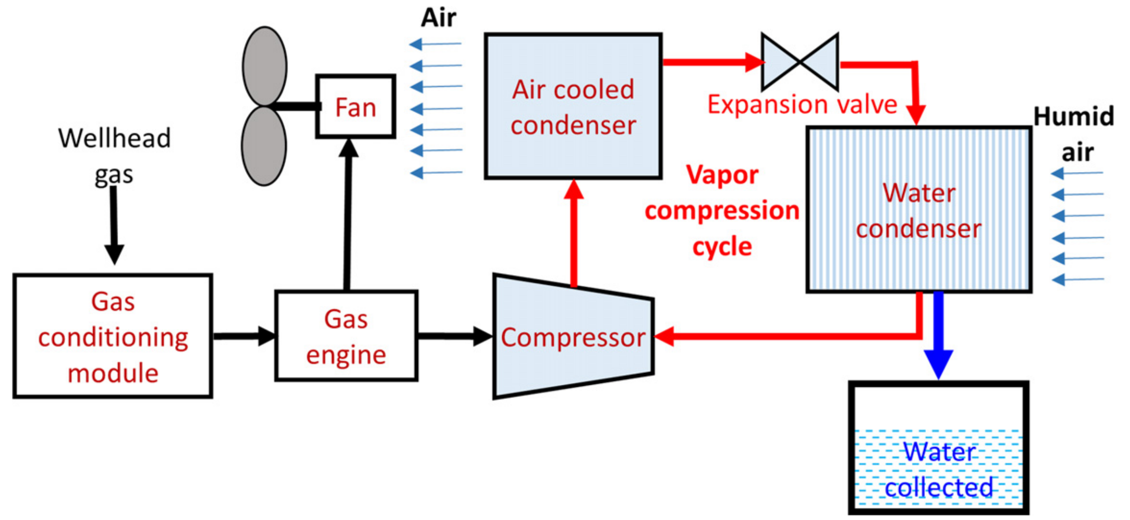

Figure 1. A gas engine-based AWH system. A natural gas-fired engine drives the compressor of the vapor compression cycle. Atmospheric moisture condensation occurs on the water condenser (evaporator of the refrigeration cycle). The latent heat of condensation is rejected to the atmosphere by the air cooled condenser.

groundwater permits is challenging because of depletion concerns in this area.

There are significant water concerns in other major Shale plays in Texas (Permian, Barnett), Pennsylvania (Marcellus), Colorado (Denver–Julesberg basin) and California (Monterey). Freshwater procurement costs in these areas ranges from 0.25 to 1 \$/barrel [22, 23] and transportation costs can be as high as \$ 5/barrel [20, 22]. An alternate way to quantify water costs is to relate them to the quantity of crude produced. Using this approach, the costs [24, 25] of sourcing and transporting freshwater range from 50 cents to several dollars per barrel of produced crude. Overall, there is unanimous agreement within industry that water will be a bottleneck for sustained development of shale resources.

This work introduces the concept of using the energy of natural gas (that would have been flared) for onsite atmospheric water harvesting (AWH) for oilfield operations. Atmospheric moisture is a largely untapped but significant freshwater source. However, water condensation is energy intensive [26] (2260 kJ l^{-1} of water), which has held back the realization of industrial scale AWH systems. Past AWH efforts [27] have focused on fog harvesting techniques, which work under limited conditions and require large collection areas. Commercial development of AWH systems [28] is limited to electricity powered units that produce hundreds of gallons of water daily, but with high electricity costs, exceeding 20 cents/gallon.

‘Free’ flared natural gas is an attractive energy source to realize large scale AWH. Incidentally, areas with high flaring activity coincide with water stressed areas, which makes this concept particularly attractive. The present work indicates that AWH can supply significant freshwater for oilfield operations. This will alleviate the pressure on existing water reserves and possibly reduce the cost of hydrocarbon production. Other benefits include less trucking traffic, reduced environmental impact and elimination of the negative press accompanying flaring. It should be noted that the water condensed from the atmosphere meets the standards for human consumption [29], which implies its suitability for oilfield operations.

3. Pathways for flared natural gas-based AWH

Various pathways to use gas (that would have been flared) to provide the cooling capacity for atmospheric moisture condensation are described in table 1. Gas powered refrigeration cycles can condense atmospheric moisture, wherein the latent heat released during condensation is used to evaporate a refrigerant. Vapor compression refrigeration systems are driven by a compressor, which generates the pressure difference to drive the cycle. Such compressors can be powered by a gas engine (option 1), gas fired steam turbine (option 2) or gas turbine (option 3). Figure 1 schematically shows a gas engine powered AWH system which utilizes a vapor compression cycle. Natural gas from the wellhead is fed to a gas engine after cleanup in a gas conditioning module, which could include knockout drums and scrubbers. The gas engine powers the compressor of the refrigeration cycle. The evaporator of the cycle consists of a bundle of tubes or plates with refrigerant evaporating on the inside and moisture condensing on the outside from the humid air flowing over it. The latent heat released during condensation is ultimately rejected to the air by the air cooled condenser.

Table 1. Pathways for flared gas-based atmospheric water harvesting. The last two columns show estimated daily water production in the Eagle Ford and Bakken Shales, respectively.

Technology	Description of pathway	System COP (cooling capacity/ energy input)	Maximum daily water production from gas flared per well in the Eagle Ford in gallons (barrels)	Maximum daily water production from gas flared per well in the Bakken in gallons (barrels)
Gas engine-based vapor compression	gas → engine → compressor (vapor compression cycle) → cooling → condensation	0.67	20 160 (480)	12 120 (290)
Steam turbine-based vapor compression	gas → boiler → steam → turbine → compressor (vapor compression cycle) → cooling → condensation	0.6	18 140 (430)	11 020 (260)
Gas turbine-based vapor compression	gas → combustion chamber → generator → compressor (vapor compression cycle) → cooling → condensation	0.7	21 170 (505)	12 856 (305)
Gas-fired vapor absorption	gas → boiler → steam → absorption cycle → cooling → condensation	1	30 240 (720)	18 370 (440)
Gas heating-based desiccant dehumidification	desiccant moisture absorption from air → gas-fired burner → desiccant dehydration → water	—	—	—

Note: 1 barrel is 42 gallons.

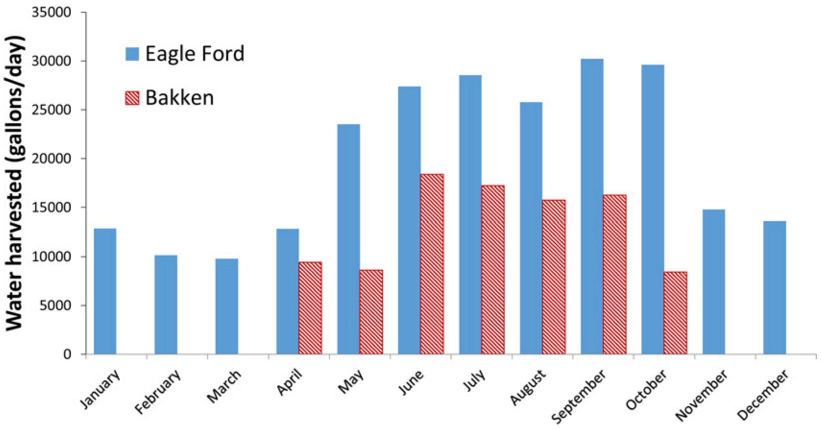

Figure 2. Annual variation of daily water harvest rate from the gas currently flared per well in the Eagle Ford and Bakken Shales. These estimates are based on the use of vapor absorption-based AWH systems and depend on flaring rates and ambient weather.

Alternatively, vapor absorption [30] refrigeration systems (option 4) can be used, which directly utilize gas-based heating to run the refrigeration cycle. The vapor absorption cycle does not require a mechanical compressor, but relies on thermal energy (heat) to create the pressure difference that drives the cycle. It is important to note that high capacity refrigeration systems (1000 tons) are commercially available [30] and would be adequate for this application. Natural gas-based heating can also be used to run desiccant dehumidification cycles [31] (option 5); however this system is less developed than other systems, and is not analyzed in detail.

A first order model to estimate water harvest rates is presented ahead. Key determinants of the water harvest rate include the flared volume, environmental conditions (temperature, relative humidity) and the gas-to-cooling pathway employed. The water harvest rate depends on the cooling capacity, which absorbs the heat released during condensation. The cooling capacity depends on the efficiency and coefficient of performance (COP) of individual system components. As an illustration, the cooling capacity q_{cooling} for the gas engine-based vapor compression system can be obtained as:

$$q_{\text{cooling}} = f\eta_{\text{engine}}(\text{HV})(\text{COP})_{\text{ref}}, \tag{1}$$

where f is the flare rate, HV is the heating value of flared gas, η_{engine} is the efficiency of the gas engine, and COP_{ref} is the COP of the refrigeration cycle. The COP represents the ratio of the cooling capacity to the total energy input (to power the compressor and fans). Table 1 also lists the system COP, which is defined as the ratio of cooling capacity to the energy input (from flared gas). Performance numbers of commercial systems are used for these estimates and are detailed in the supplementary information.

The water production rate $\dot{m}$ can be estimated from the cooling capacity as:

$$\dot{m} = \frac{q_{\text{cooling}}}{h_{\text{fg}} + (T_{\text{drybulb}} - T_{\text{sat}})\left(C_{p,\text{water}} + \dfrac{C_{p,\text{air}}}{\omega}\right)}, \tag{2}$$

where h_{fg} is the latent heat of condensation, T_{drybulb} is the dry bulb temperature, T_{sat} is the saturation temperature, C_p is the specific heat capacity, and ω is the humidity ratio (mass of water vapor per unit mass of dry air). The above equation shows that the cooling capacity is partly used for sensible cooling of the moisture and air to the saturation temperature, and then to absorb the latent heat released during condensation.

Equation (1) captures the energetics of the condensation process. It is important to size the water condenser such that adequate surface area is available for moisture condensation and drainage. The area requirements (A) of the water condenser can be estimated via the heat transfer rate equation as:

$$q_{\text{cooling}} = hA(T_{\text{sat}} - T_{\text{s}}), \tag{3}$$

where h is the condensation heat transfer coefficient, T_{sat} is the saturation temperature and T_{s} is the temperature of the evaporator surface. It is seen that higher saturation temperatures will enable higher AWH yields. Heat transfer coefficients were estimated using existing correlations and details are provided in the supplementary information.

The above equations were used to predict water harvest rates based on the flare rates and ambient conditions. To account for the variability in temperature and humidity, month averaged daytime and nighttime temperature and relative humidity data [32] was used to estimate water harvest amounts over 12 hour intervals. These harvest rates were added to arrive at estimates of annual water harvest.

4. Results—estimated water harvest rates

Table 1 shows the daily water production using the gas currently flared per well in the Eagle Ford (340 MCFD)

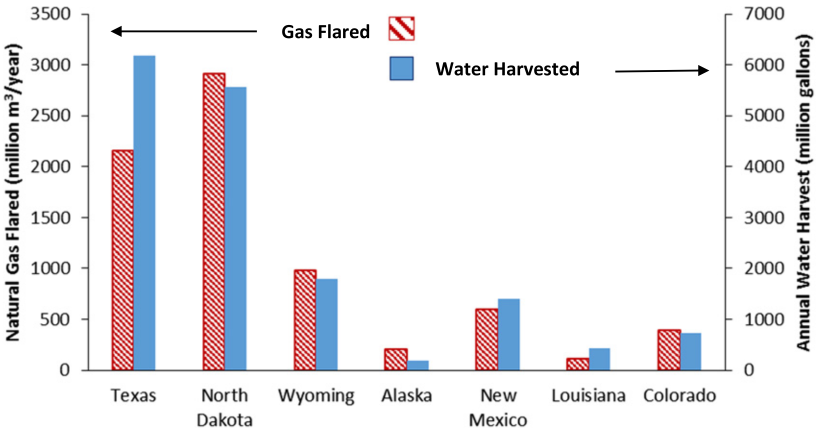

Figure 3. Total annual flaring and water harvest estimates in seven US states with significant flaring. These estimates are based on the use of vapor absorption-based AWH systems and depend on the flared volume and ambient weather.

Table 2. Flared gas volumes and the water harvest in select countries with high flaring activity. The significance of the quantity of water harvested is quantified by comparing it with domestic water consumption in leading cities.

Country	Gas flared in 2011 [2] (billion m^3)	Annual AWH harvest (billion gallons)	Significance of quantity of AWH water
Russia	37.4	77.2	Domestic consumption [34] of Moscow for 3 months
Nigeria	14.6	58.4	Domestic consumption [35] of Lagos for 3 years
Iran	11.4	21.2	Domestic consumption of Tehran [36] for 1 months
USA	7.1	20.3	Domestic consumption of Houston [37] for 1 week
Angola	4.1	16.3	Domestic consumption of Luanda [35] for almost 2 years
Saudi Arabia	3.7	6.5	Domestic consumption of Riyadh [38] for over 2 weeks
Mexico	2.1	8.3	Domestic consumption of Mexico City [35] for 1 week

and the Bakken (195 MCFD). Up to 30 240 gallons/day/well (720 barrels/day/well) can be harvested using a vapor absorption cycle-based system in the Eagle Ford. The AWH yield in the Bakken is 18 370 gallons/day/well (440 barrels/day/well). It is seen that the vapor absorption-based system has the highest yield (details in the supplementary information) of all the systems in table 1. Vapor absorption systems are also more reliable than vapor compression systems due to the absence of a mechanical compressor.

The obtained harvest rates are significant in view of the high freshwater costs. It should be noted that the numbers in table 1 are based on average flare rate per well in the Eagle Ford and the Bakken. Many production sites have multiple wells that are flared, which will increase the total water output. As an illustration, there are 50 locations [8] in the Bakken with flare rates exceeding 1200 MCFD, which can yield 112 600 gallons d^{-1}. More granular details on flaring rates within the Eagle Ford and the Bakken are not publicly available.

Figure 2 shows monthly variations in the daily water production rate per well (vapor absorption system) in the Eagle Ford and the Bakken. Significant quantities of water can be harvested all year round in Texas, with the harvest rate peaking in summer when other water sources decline. It should be noted that there is no water harvest during the winter months in North Dakota when the ambient temperature is below freezing. However, the yields in summer indicate that AWH is attractive not only for hot, humid regions, but in colder northern latitudes as well.

Figure 3 quantifies the annual AWH yields in seven US states, based on the flaring [1, 33] and weather [32] in these states. It is seen that water harvest rates can be substantial in many states with Shale resources. As an illustration, 100% of the wells in the Denver–Julesberg basin in Weld County, Colorado are located in an extreme water stress region [14]. Based on the annual water harvest (figure 3), the gas flared from Weld County alone can condense enough water to hydraulically fracture 750 wells. Similar benefits exist in other states including Wyoming and New Mexico. It should be noted that this concept has marginal benefits in Alaska, since the low temperatures preclude high AWH rates. It is important to note that the flaring quantities in these states are from Shale production only and do not include gas flaring from offshore operations.

Table 2 highlights the global potential of flared gas-based AWH by quantifying the annual water production in select high flaring countries [2]. Water harvest rates are estimated from the flared gas quantity and 12 hour day and night averaged weather

Table 3. Benefits of flared gas-based onsite AWH for the Eagle Ford and Bakken Shale (all figures are annual). These values are based on AWH yields and water requirements for hydraulic fracturing and drilling.

Parameter	Eagle Ford Shale	Bakken Shale
Flaring [3] in billion cubic feet	34	96
AWH production (billion gallons)	2	3.9
Percentage of water requirement that can be met via flared gas-based AWH	11%	65%
Number of wells that can be hydraulically fractured with AWH water	470	1750
Number of existing wells (oil and gas) [14]	4310	2 830
Number of days to harvest enough water to fracture a new well using the gas flared per well	141	120
Number of wells that can be drilled with AWH water	8010	14 030
Number of days to harvest enough water to drill a new well using the gas flared per well	9	15
Number of trucking roundtrips saved/well [6]	765	400

conditions [32], using the methodology described earlier. It is seen that atmospheric water production can make a significant contribution towards meeting domestic water consumption requirements. It should be noted that this analysis does not consider the challenges associated with collecting water over huge distances. However it does highlight the global benefits of this concept.

5. Economic benefits of flared gas-based AWH

An overview of the benefits of flared gas-based AWH for the Eagle Ford and Bakken Shales is provided in table 3. Overall, 2 and 4 billion gallons water can be harvested annually in the Eagle Ford and the Bakken Shales respectively. This will meet 11% and 65% of the annual water consumption in the Eagle Ford [13] and Bakken [13] respectively. This water could be utilized to hydraulically fracture or drill new wells. The gas flared from a well alone can harvest enough water to fracture a new well in 4 months in the Bakken. For the 50 sites in the Bakken [8] with much higher flaring rates (exceeding 1200 MCFD), the gas flared per site can harvest enough water to fracture a new well in only three weeks. This timeframe is consistent with the fact [6] that newly completed wells have very high flaring rates in the first few weeks and months. This implies that with proper planning, AWH can meet 100% of the water requirements for hydraulic fracturing of a significant number of wells planned for the future, as detailed in table 3.

The benefits of flared gas-based AWH are amplified if the water is used for drilling operations. Drilling is less water intensive than hydraulic fracturing, with a drilling operation requiring an average of 250 000 gallons/well [15]. Table 3 shows that the gas flared per well can harvest enough water to drill a new well in only 9 and 15 days in the Eagle Ford and the Bakken respectively. Additional benefits of AWH to the local communities include reduced truck traffic, accidents, and elimination of light and environmental pollution. Overall, flared-gas based AWH in the Eagle Ford and Bakken can eliminate 2 million and 5 million trucking roundtrips annually, respectively.

The data in table 3 can be used to quantify the cost savings potential of onsite AWH. In the Eagle Ford and the Bakken, the cost of procuring [22, 23] and transporting [22, 23] freshwater can reach $ 1/barrel and $ 5/barrel respectively. The cost savings based on data from table 3 can be significant to warrant industry interest, noting that water-related costs [25] account for 5%–10% of a wells total cost. Eventual deployment of AWH systems at a particular site is contingent on a favorable cost benefit analysis. Detailed analyses are beyond the scope of the present work since such data is very location specific and not publicly available.

6. Perspectives on AWH and challenges

While the previous sections outline the enormous global potential of AWH, it is important to discuss the challenges underlying the deployment of AWH systems. These challenges include the presence of competing technologies and technical challenges. Alternatives to AWH include the practice of recycling and reuse of flowback and produced water. Flowback water utilization [39] is becoming increasingly common in the industry. However it is currently not widely utilized in the Eagle Ford [40] and the Bakken [14] due to high water treatment costs in those fields. Flowback rates can range from 20% to 40% of the pumped water, so large quantities of freshwater will still be required. With this in mind, flared gas-based AWH should be viewed as another tool in the basket of water solutions.

It should be noted that high utilization rates of flared gas would hinge on the availability of sufficient capacity of the gas conditioning system and the refrigeration modules. It should also be noted that flaring emissions are variable and not steady. The use of mobile modular AWH units which can be daisy-chained, and the availability of onsite spare capacity are potential solutions to ensure high utilization rates. Capacity planning and equipment sizing are important considerations that determine the capacity factor, which would be a measure of the fraction of gas that is used for AWH.

Certain technical challenges need to be overcome to improve the value proposition of AWH systems. The capital expenditures for AWH systems can be reduced by making the water condenser more compact. Heat and mass transfer analyses [41] of moisture condensation indicate that the harvest rate in the Eagle Ford can approach ~100 gallons/day/square meter under the most favorable weather conditions in July. Such analyses provide an indication of the size of AWH systems required for a particular location. Equation (3) shows that low condensation heat transfer coefficients necessitate large condenser areas, which drives up equipment size and cost. In existing condensers, water condenses as a film [42] which acts as a thermal barrier and significantly decreases heat transfer. Heat transfer can be enhanced by exploiting drop-wise [42] condensation, wherein water drops condense and roll off, thereby exposing the surface to fresh air. Superhydrophobic [42] coatings facilitate drop-wise condensation and can enable an order of magnitude enhancement in heat transfer [42], which will reduce the water condenser size. Another challenge with compact water condensers is the requirement to drain large quantities of condensed water to prevent performance degradation. Additionally, it is important to minimize the size and weight of the air cooled condenser which eventually rejects the heat from condensation.

The target for the compactness of AWH systems can be extracted from the need to develop mobile, portable AWH units. Mobile AWH units are critical to technology adoption since most flaring occurs only in the first few months of a well's life. This short time span would eliminate the economic incentives to setup permanent AWH infrastructure.

Ultimately, the deployment of AWH systems at a particular site will be contingent on favorable techno-economic analysis, which involves details of capital expenditures, equipment depreciation rates, labor costs, compliance and permitting costs, and projections of the benefits. It should also be noted that gas flaring also serves a safety purpose and AWH systems will need to be assessed from that angle.

Beyond flared gas utilization, the proposed approach can also be coupled to flue gas-based water harvesting systems [43]. Such systems can extract water from the combustion stream (primarily water vapor and carbon dioxide) of AWH systems, with additional energy input. Carbon capture technologies [44] (to absorb CO_2 from the emissions) could also be integrated for greater environmental benefits. The proposed concept also offers an alternative to desalination in regions which significant flared volumes, but which lack brackish water sources. All such possibilities and applications deserve detailed analysis and assessment.

7. Conclusions

This work presents a novel solution to a global environmental and resource wastage problem. It is seen that flared gas-based AWH can meet 11% and 65% of the annual water requirements of the Eagle Ford and Bakken Shales. This water is sufficient to drill 22 000 wells, or frac 2200 wells, and will eliminate upto 7 million trucking roundtrips in these two states. Flared-gas based AWH has promising potential in other high humidity, high flaring regions like the Middle East, Africa and Central America (Mexico, Venezuela). Beyond flared-gas utilization, this concept enables a new market for natural gas at a time when the demand for gas is low. The worldwide abundance of natural gas highlights the potential global benefits of natural gas-based AWH. Key challenges to further development of this concept include the need for mobile systems, capacity planning and logistical challenges, and other competing technologies.

Acknowledgments

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