EPA Hydraulic Fracturing Study Technical Workshop #4
Water Resources Management
March 29-30, 2011

NATURAL GAS: FUELING AMERICA'S FUTURE

Produced Water Reuse and Recycling Challenges and Opportunities Across Major Shale Plays

Matthew E. Mantell, P.E.
Environmental Engineer
Engineering Technology Group

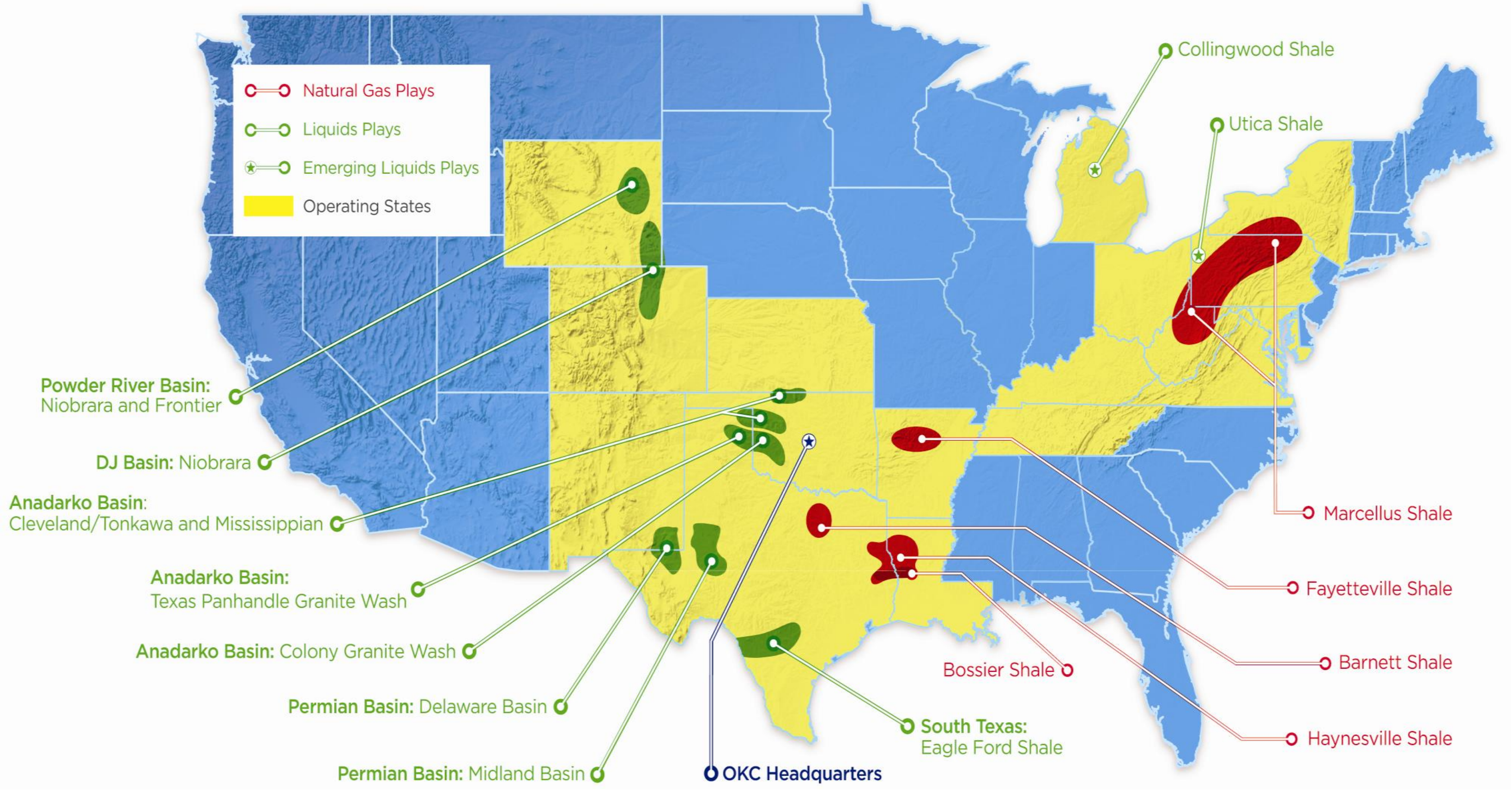
Chesapeake Energy Corporation
6100 N. Western Avenue | Oklahoma City, OK 76118 | 405-935-8000
AskChesapeake@chk.com | chk.com | NYSE: CHK

Presentation Overview

- Introduction
  - Chesapeake Operating Areas
  - Water Use by Shale Play
- Produced Water Management
  - Produced Water Naming Conventions
  - Generation of Produced Water by Play
  - Produced Water Quality and Issues
- Produced Water Management Options
  - Direct Filtration and Reuse
  - Deep Well Disposal
  - Advanced Treatment for Reuse
- CHK Experience with Water Reuse/Recycling
- Criticisms of Shale Gas Water Use
- Closing Thoughts

Additional information on water efficiency of shale gas presented in Appendix

Chesapeake Energy Operating Areas



Current Chesapeake Water Use by Shale Play

Chesapeake ENERGY

Gas Shales (Dry Gas)

Barnett Shale*

250,000 Gallons used for Drilling
3,800,000 Gallons used for Fracturing

~ 4.0 Million Gallons Used Per Well

Fayetteville Shale

65,000 Gallons used for Drilling
4,900,000 Gallons used for Fracturing

~ 4.9 Million Gallons Used Per Well

Haynesville Shale

600,000 Gallons used for Drilling
5,000,000 Gallons used for Fracturing

~ 5.6 Million Gallons Used Per Well

Marcellus Shale*

85,000 Gallons used for Drilling
5,500,000 Gallons used for Fracturing

5.6 Million Gallons Used Per Well

Liquid Shales (Gas, Oil, Condensate)

Eagle Ford Shale

125,000 Gallons used for Drilling
6,000,000 Gallons used for Fracturing

~ 6.1 Million Gallons Used Per Well

Niobrara

300,000 Gallons used for Drilling
3,000,000 Gallons used for Fracturing

~ 3.3 Million Gallons Used Per Well

* Portion of play contains some NG liquids

Produced Water Management

Produced Water Naming Conventions

“Produced Water”

- ALL water that is returned to the surface through a well borehole
- Made up of water injected during fracture stimulation process as well as natural formation water
- Typically is produced for the lifespan of a well (quantities vary significantly by play)
- Produced water is chemically analyzed prior to reuse / recycling or disposal
  - Analyzed for hydrocarbons, metals, and naturally occurring elements
- Water quality varies:
  - “Brackish” (5,000 to 35,000 ppm TDS)
  - “Saline” (35,000 to 50,000 ppm TDS)
  - “Brine” (50,000 to 150,000+ ppm TDS)

Produced Water Naming Conventions

“Flowback” Process

- Term associated with the PROCESS
- Process allows the well to flow back excess fluids and sand
  - Once sand and fluid have been removed, gas and/or petroleum liquids begin to flow (the purpose)
  - Flowback process equipment is designed to handle heavy solids
  - Permanent equipment put in place when process is complete
- Actual duration of the process varies from well to well and play to play
- The distinction of “flowback water” and “produced water” has nothing to do with water quality.
- ALL “flowback water” IS “produced water”

Produced Water Generation by Shale Play: Initial Produced Water

- **Quantities and Rates of Water Production Important for Reuse**
  - Need large volume of water over short time period
    - Helps ensure the effectiveness of the process
  - "Initial" defined here as first 10 days of Flowback and Production Process
- **Barnett, Fayetteville, and Marcellus Shales**
  - "Initial" volume of water significant
    - 500,000 to 600,000 gallons per well in first 10 days → ~ 10% to 15% of total water need to frac new wells
- **Haynesville Shale**
  - "Initial" volume of water less significant
    - 250,000 gallons per well in first 10 days → ~ 5% of total water needed to frac new well

Still collecting data on "initial" water production data on Niobrara and Eagle Ford Wells

Produced Water Generation by Shale Play: Dependant on Geology of Shale Formation

- **High “Long Term” Produced Water Generating Play (> 1,000 Gallons Per MMCF)**
  - Barnett Shale:
    - Formation characteristics result in high produced water generation
    - Higher volumes of natural formation water present in / near shale
- **Moderate “Long Term” Produced Water Generating Plays (200 – 1,000 Gallons Per MMCF)**
  - Eagle Ford Shale
  - Haynesville Shale
  - Fayetteville Shale
    - Formation characteristics allow less fluid production per MMCF
    - Relatively desiccated formations (dry)

- **Low “Long Term” Produced Water Generating Play (< 200 Gallons Per MMCF)**
  - Marcellus Shale
  - Higher water production in South (West Virginia), lower in North (Pennsylvania)
    - Shale formation characteristics tend to “trap” fluids
    - Highly desiccated formations (very dry)
    - Capillary pressure difference “binds” water to formation (known as imbibition)

Salt Water Disposal wells may still be needed to manage and dispose of long term produced water

Water Quality and Treatment / Reuse

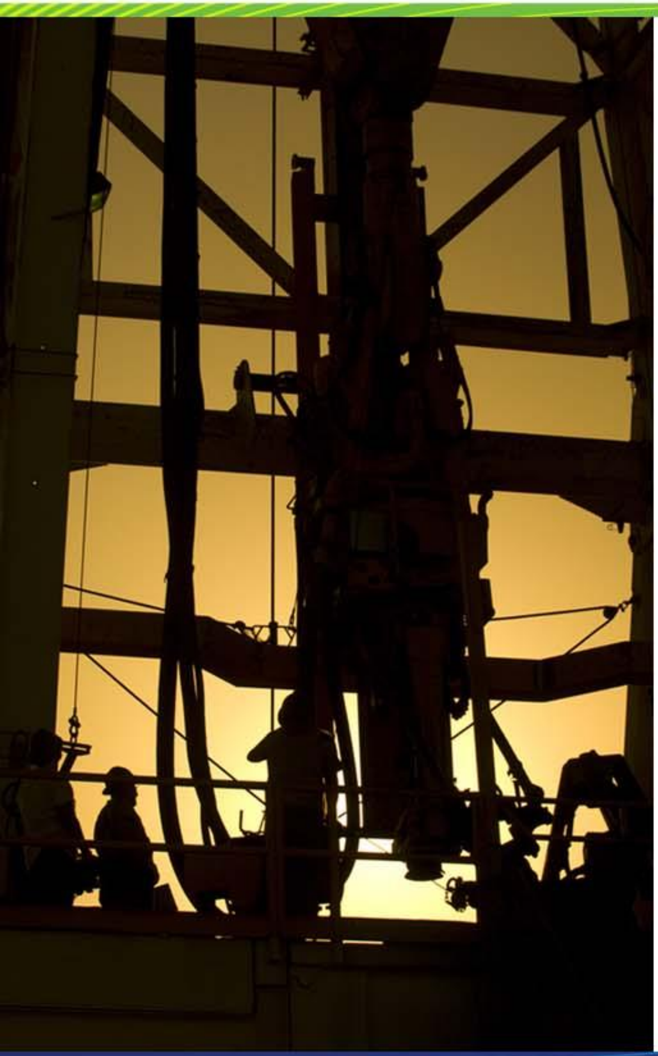
- **Dissolved Parameters → Blending for Reuse**
  - Chlorides and Total Dissolved Solids (TDS)
  - Generally not looking at removal, determines freshwater blending ratios
  - Very high TDS increases friction in hydraulic fracturing process (bad)
- **Suspended Parameters → Filtering Prior to Reuse**
  - Turbidity and Total Suspended Solids (TSS)
  - Can determine filtration rates, size of filter, performance
  - High solids can plug well and decrease biocide effectiveness
- **Other Parameters of Concern**
  - Water "hardness" compounds (e.g. Calcium and Magnesium)
  - Sulfates can be used by bacteria to create hydrogen sulfide
  - Barium can combine with sulfates to create scale
  - High iron can drop out creating emulsions and plugging
  - Bacteria is always a concern

"Frac Tanks" on location

Initial and Produced Water Quality Data: Barnett and Fayetteville Shales

- **Barnett Shale**
  - Significant increase over time in TDS (50,000 → 140,000 ppm) and Chlorides (25,000 → 80,000 ppm); initial produced water is relatively low
  - Relatively low TSS, no problem for filtration
  - Iron values are relatively low compared to other plays, but still pose concern
- **Fayetteville Shale**
  - "Good Quality Water" on both initial and long-term → very low Chlorides (~ 10,000 ppm), low TDS (~ 15,000 ppm)
  - Lower scaling tendency (low Calcium, low Magnesium)
  - Excellent potential for reuse of both initial and long term produced water

Initial and Produced Water Quality Data: Haynesville and Marcellus Shales



- **Haynesville Shale**
  - Immediately after frac, very poor quality water → high TDS, high Chlorides, high TSS (~350 ppm)
  - High scaling tendency → high calcium (~8,000 ppm) and high magnesium (~500 ppm)
  - Relatively unattractive reuse potential
- **Marcellus Shale**
  - Immediately after frac, high TDS (40,000 ppm -- 90,000 ppm with long term > 120,000 ppm)
  - However, lower TSS values (~160 ppm) make filtration reasonable
  - Moderate to high scaling tendency (high Ca, Mg)
  - Quality is manageable and attractive for reuse

Eagle Ford Shale and Niobrara currently being evaluated for reuse: definite potential!

Chesapeake ENERGY

Produced Water Management Options

Preferred Practice: Filtration and Reuse CHK's Marcellus Shale Program Example

Process

1. Produced water during "flowback" process collected and stored in holding tanks onsite
2. Produced water pumped from tanks through a 100-micron filter followed by a 20-micron filter
   – Filter is designed to remove suspended solids in fluid (not salts)
3. Filtered fluid is pumped into a clean storage tank and transported to next well to be hydraulically fractured
   – Filters and solids collected are disposed of by a licensed contractor and sent to an approved landfill
4. Prior to use in frac, the water is tested for remaining constituents (TDS/Salts, Scaling Compounds) that were not removed in filtration process
   – Test results determine blending ratios
   – Robust scale inhibition and bacteria elimination programs implemented which require substantial management and testing prior to frac
5. Fresh "make-up" water is still required to ensure adequate quality and quantity of fluids

Preferred Practice: Filtration and Reuse CHK's Marcellus Shale Program Example

Benefits

1. Reduction in the volume of wastewater
   - Less sent offsite for disposal
2. Less fresh water needed for hydraulic fracturing operations
   - Reduced impact on local supplies
3. Reduced truck traffic on public roads (less fresh water hauled)
   - Lower impact on public roads, noise, air quality
4. Filtration process used is inexpensive and does not require substantial amounts of energy like other processes that remove salts (i.e. reverse osmosis membranes, distillation)
5. Helps reduce the cost of operations
   - Reduces wastewater disposal costs, water supply costs, and transportation costs

Advanced Treatment and Reuse Not Always the Environmental Option

- **Environmental and Economic benefits may directly correlate when evaluating reuse versus disposal**
  - REUSE $$ = ENERGY $$ + TRANSPORT $$ + CONCENTRATED WASTE DISPOSAL $$
  - DISPOSAL $$ = TRUCKING $$ + DISPOSAL $$
- **Where Direct Reuse is Not Feasible Due to Water Quality, Logistics**
  - Injection Wells are low cost, low energy, safe, and effective
  - Energy requirements for treating some fluids make these techniques economically unfeasible, and ALSO environmentally undesirable
    - Air Emissions
    - Water use
    - Waste

Chesapeake Energy does not surface discharge any produced water either directly, or via wastewater treatment plants

Advanced Produced Water Treatment Options

- **Thermal Distillation**
  - Ability to treat produced water and recapture distilled water
  - Beneficial in times of drought or in arid areas
  - Very energy intensive (and costly)
  - Most distillation systems are designed for treatment of large volumes of water
    - Larger Centralized Facilities
    - Long Hauling Distances
- **Membrane Systems (Reverse Osmosis)**
  - Very prone to scaling without comprehensive pretreatment
  - Need very experienced operators
  - Technology is improving → coatings, etc
  - Energy intensive → but less than Thermal Distillation
- **Chemical Precipitation and Electro-Coagulation**
  - Less expensive but still requires relatively experienced operators

Beware of the Black Box!

Produced Water Reuse and Recycling: The Chesapeake Experience

Intevras' EVRAS unit at the Brentwood site in east Fort Worth

Barnett Shale Reuse / Recycling

- **Blessed with Extensive SWD Infrastructure**
  - Injection into Ellenberger formation
- **Currently Reusing Approx 230,000 Gallons Per Well in southern portion of the play**
  - Partial Reuse Makes Economic Sense
  - Reuse makes up ~ 6% of total water needed to hydraulically fracture a new well
  - Logistics and economics are the main limiting factor in preventing higher levels of reuse
- **CHK Pioneering Use of Evaporative Technologies that Utilize Waste Heat in the Barnett**
  - INTEVRAS Evaporative Unit
    - Less water (as concentrated brine) injected in SWD well onsite

Fayetteville Shale

- Very good water quality (low TDS, chlorides) as compared to other plays
  - TDS in 10,000 to 20,000 ppm range
- Currently reusing approx 250,000 gallons (80% of initial produced water) per well
- Reuse makes up ~ 6% of the total water needed to hydraulically fracture a new well
- Good produced water quality makes reuse of long term produced water possible if logistics make sense

Haynesville Shale

- Extensive SWD Infrastructure in East Texas
- Currently, CHK is not reusing HS produced water
- Poor produced water quality (even initially)
  - High TDS, high solids, high scaling tendencies
- Relatively low volume of initial produced water
  - 250,000 gallons over 1st ten days (low)
  - Water production falls off quickly
- Large volumes and higher quality drilling wastewater currently make it a more feasible reuse candidate

Marcellus Shale

- **Currently recycling / reusing nearly 100% of initial produced water via improved filtering processes**
  - Reduces produced water disposal volumes by approx 85% to 100%
  - Tremendously successful program
  - Remaining fluids (long term produced water, etc) sent to Salt Water Disposal wells
  - Small volume (<1%) sent to advanced treatment and reused
- **Reuse makes up ~ 10% of the total water needed to hydraulically fracture a new well**
- **Use closed loop synthetic oil based muds**
  - Significantly reduces wastewater generated from drilling

Chesapeake Energy does not surface discharge any produced water either directly, or via wastewater treatment plants

Chesapeake ENERGY

Oil and Natural Gas Water Use Concerns

Criticism of Oil and Natural Gas Water Use

- **Concerns of the so called "permanent removal of water from the effective hydrologic cycle**
  - Most water used in shale gas development either remains in the formation or returns as produced water
  - The preferred method for disposal of produced water is through permitted Class II SWDs
  - Argument that this is a different type of "consumption" than the evaporation of water from a power plant and other types of "consumption"

Natural Gas Combustion: Water Vapor Generation

- **Balanced Methane Combustion Reaction:**

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$$

- **Volume of Water Vapor Produced per Million Cubic Feet of Natural Gas:**
    - 10,675 gallons

- **Need to combust 525 MMCF of natural gas to produce an equivalent amount of water (as vapor) used to drill and complete a typical Marcellus Shale well**
    - Based on current production trends, it takes an average CHK Marcellus Well < 6 months to produce 525 MMCF of Natural Gas

* Not all natural gas that is consumed is combusted. According to 1995 DOE Topical Report, approximately 3.5% of natural gas is used as feedstock for ammonia, methanol, and ethylene production.

Closing Thoughts

1. U.S. Oil and Natural Gas Industry is REDUCING* the volume of freshwater used in operations → reducing the need to compete with other freshwater users
2. Feasibility of Produced Water Reuse is dependent on 3 factors: quantity, duration, and quality
3. All three factors (quantity, duration, quality) can vary considerably between / within shale plays
4. Environmental and Economic Benefits may directly correlate when evaluating reuse versus disposal options
5. Volume of water "removed" from hydrologic cycle during fracturing or deep well disposal is more than offset during the combustion of fuel

** More importantly the industry is improving the efficiency of fresh water use (i.e. more hydrocarbon production per unit of fresh water utilized)*

Produced Water Reuse and Recycling Challenges and Opportunities Across Major Shale Plays

Matthew E. Mantell, P.E.
Corporate Environmental Engineer

Chesapeake Energy Corporation
6100 N. Western Avenue | Oklahoma City, OK 76118 | 405-935-8000
AskChesapeake@chk.com | chk.com | NYSE: CHK



Appendix: Water / Energy Nexus: The Water Efficiency of Energy Resources

The Water / Energy Nexus

- **"Water is Essential for Energy Resource Development"**
  - Fuel Extraction
  - Fuel Processing
  - Power Generation Cooling

- **"Energy Resources are Needed for Water"**
  - Development (raw water pumping)
  - Processing (treatment)
  - Distribution (potable water pumping)
- **"Balance" or "Nexus" is *Critical* but Often *Overlooked* when evaluating Energy Resources**
  - Many discussions on air quality and surface pollution impacts
  - Limited discussion on water availability
  - Improve One → Improve the Other

Water Use Efficiency in Natural Gas Plays

Chesapeake ENERGY

Chesapeake's Four Major Deep Shale Plays

Shale Play	Average Water Use Per Well [1]	CHK Est. Avg. Natural Gas Production Over Well Lifetime [2]	Resulting Energy From Natural Gas Production Per Well (based on 1,028 Btu per Cubic Feet)[3]	Water Use Efficiency (in gallons per MMBtu)
Haynesville	5.6 million gallons	6.5 billion cubic feet	6.68 trillion Btu	0.84
Marcellus	5.6 million gallons	5.2 billion cubic feet	5.35 trillion Btu	1.05
Barnett	4.0 million gallons	3.0 billion cubic feet	3.08 trillion Btu	1.30
Fayetteville	4.9 million gallons	2.6 billion cubic feet	2.67 trillion Btu	1.84

Source: [1]Chesapeake Energy 2009b, [2]Chesapeake Energy 2009c, [3]USDOE 2007
British Thermal Unit (Btu)
Million British Thermal Units (MMBtu)

Raw Fuel Source Water Use Efficiency

Energy resource	Range of gallons of water used per MMBtu of energy produced
Chesapeake deep shale natural gas *	**0.84 – 1.84**
Conventional natural gas	1 – 3
Coal (no slurry transport) (with slurry transport)	2 – 8 13 – 32
Nuclear (processed uranium ready to use in plant)	8 – 14
Conventional oil	**8 – 20**
Synfuel - coal gasification	11 – 26
Oil shale petroleum	22 – 56
Oil sands petroleum	27 – 68
Synfuel - Fisher Tropsch (Coal)	41 – 60
Enhanced oil recovery (EOR)	21 – 2,500
Biofuels (Irrigated Corn Ethanol, Irrigated Soy Biodiesel)	**> 2,500**

Source: USDOE 2006 (other than CHK data)
*Does not include processing which can add from 0 - 2 gallons per MMBtu
Solar and wind not included in table (require virtually no water for processing)
Values in table are location independent (domestically produced fuels are more water efficient than imported fuels)

Fuel Source Water Use Efficiency

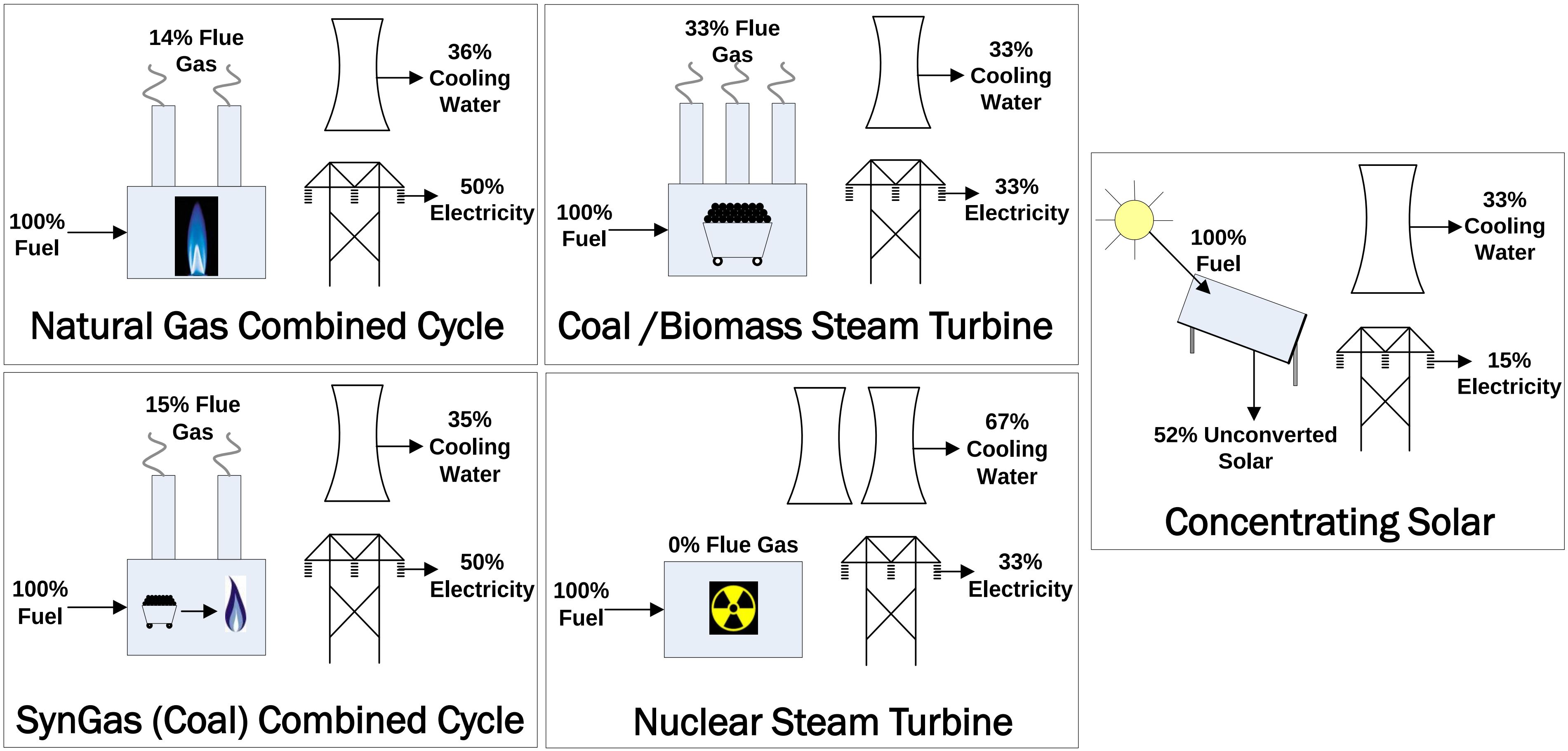
Wind and solar notes

- **Solar and wind power not included in previous table**
  - Require virtually no water for processing
  - Most water efficient
  - Currently not “baseload” worthy
    - Wind: 0.5% of all U.S. energy in 2008
    - Solar: 0.1% of all U.S. energy in 2008

Raw Fuel Source Water Use Efficiency: Geography / Location

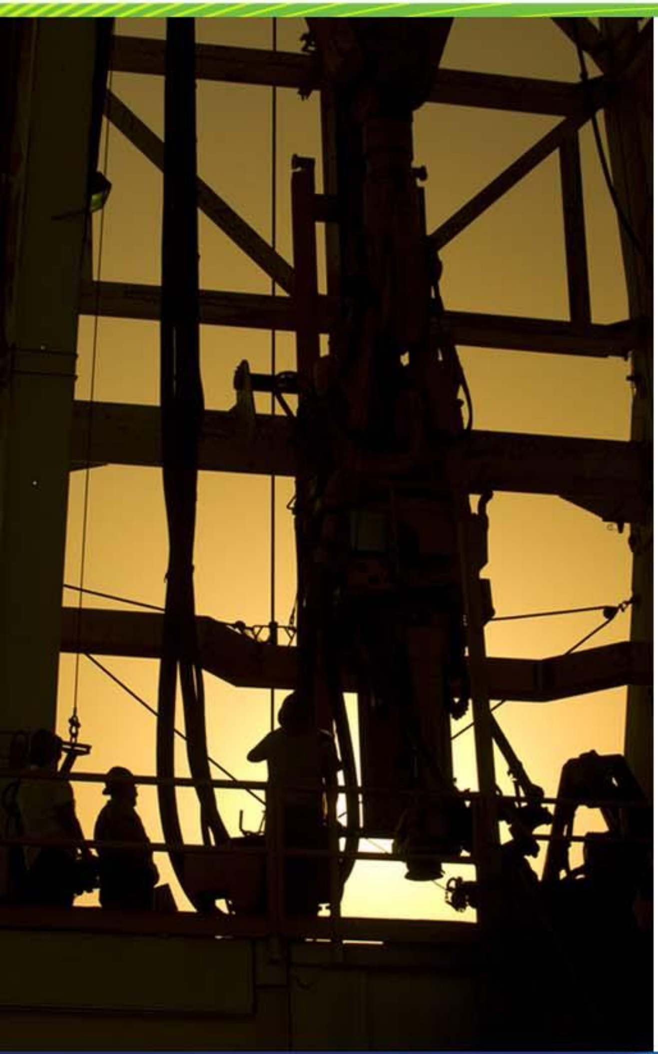
- **Geography Plays Important Role in Fuel Source Water Efficiency**
  - Values in table are location independent
  - Energy demands of fuel transport not considered
  - If considered:
    - Locally produced fuels would be given higher “value”
    - Imported fuels less water efficient → lower “value”
      - Foreign Oil, Alaskan Oil and Gas, Off-Shore Oil and Gas

Typical Efficiencies of Thermoelectric Power Plants



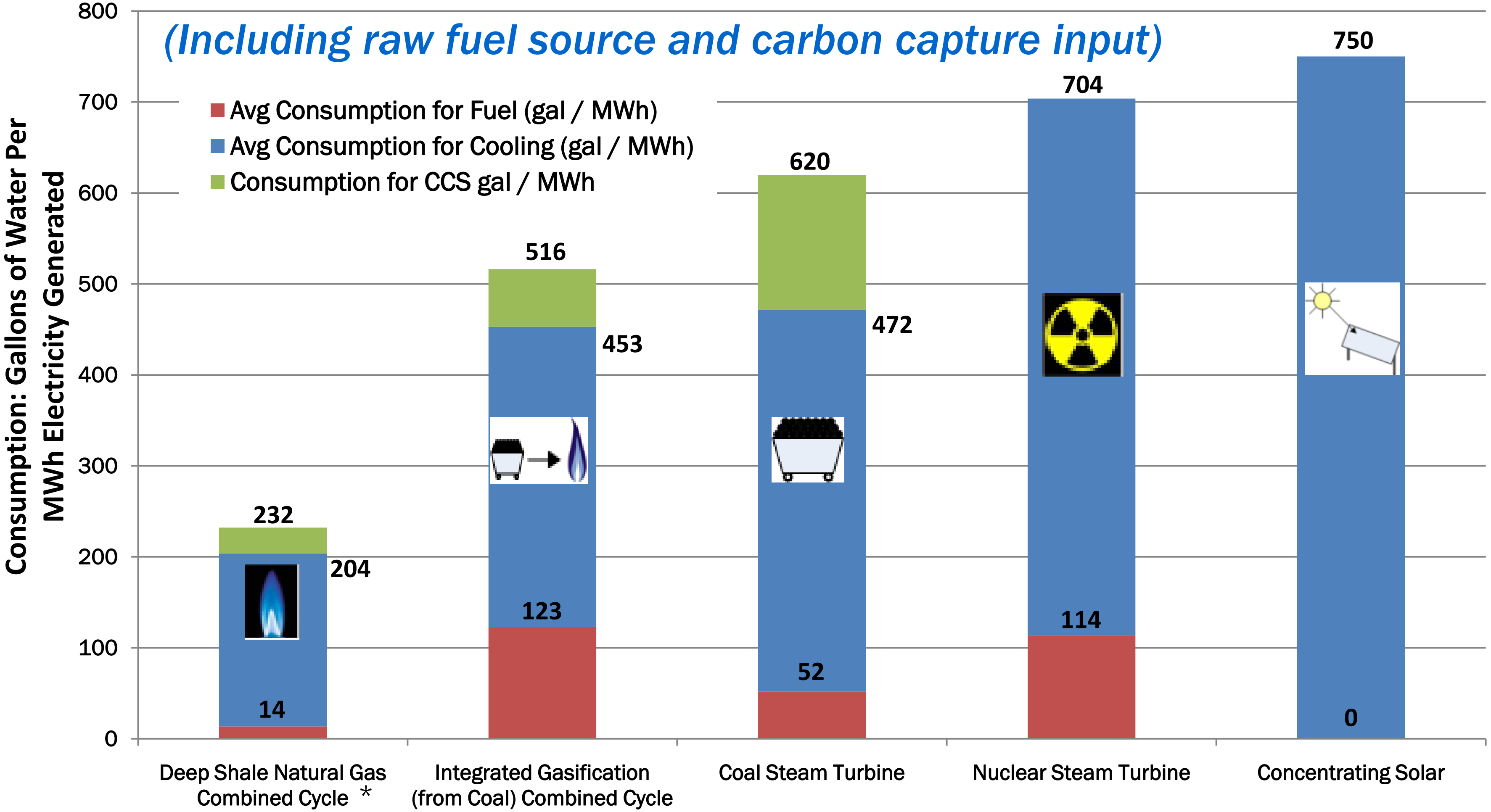
Source: Adapted from Stillwell et al. 2009

Carbon Capture and the Parasitic Effect on Power Generation and Water Use



- **Three of the power plant types evaluated emit CO_2**
  - Natural Gas Combined Cycle (NGCC)
  - Integrated Gasification (SynGas from Coal) Combined Cycle (IGCC)
  - Coal / Biomass Steam Turbine
- **Believed technological solution is the use of carbon capture, (combined with deep geological sequestration)**
- **Commonly overlooked in the discussion of carbon capture is the parasitic effect the carbon capture technology has on power generation efficiency**
- **When the efficiency of a power plant is decreased, additional generating capacity must be brought online to maintain the plant's previous electrical output**
- **Results in a reduction of the water efficiency of power plants that incorporate carbon capture**

Power Generation Water Use Efficiency
Parasitic Effect of Carbon Capture



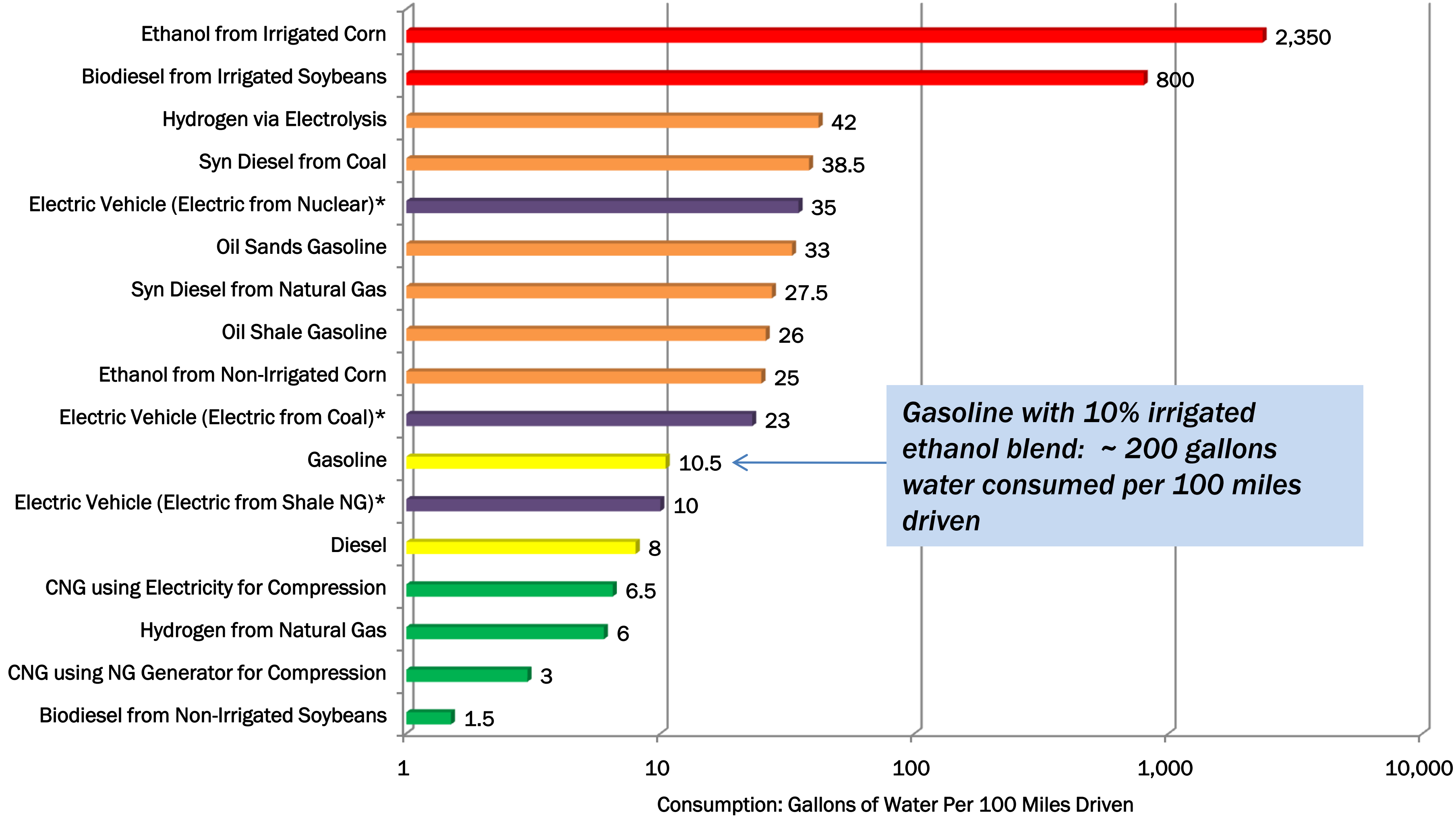
Source: USDOE 2006 (other than CHK data) and USDOE/ NETL 2007
*Average consumption for fuels; Chesapeake data
MWh = megawatt-hour

Transportation Fuels and Water Use

- **Conventional Petroleum and Gasoline Dominate U.S. Market**
  - 97% of all fuels
  - Some contain 10% ethanol blend to reduce air emissions
- **Currently Looking at “Unconventional” and “Alternative” Fuels**
  - Non-Conventional Liquid Fossil Fuels (fuels from coal, oil shale, tar sands)
  - Biofuels (ethanol, biodiesel)
  - Compressed Natural Gas
  - Hydrogen (carrier source)

- **Major “Push” to Electric Vehicles**
  - Major focus of research and development
  - Perceived to be “green” (how is electricity generated?)
  - Increase in water use “overlooked”

Water Intensity of Transportation Fuels



Compressed Natural Gas (CNG)
Source: Adapted from King and Webber 2008a;
*Adapted from King and Webber 2008b, combined with data from USDOE 2006
Non-irrigated biofuels not shown on plot above



Chesapeake ENERGY

Produced Water Reuse and Recycling Challenges and Opportunities Across Major Shale Plays

Matthew E. Mantell, P.E.
Corporate Environmental Engineer

Chesapeake Energy Corporation
6100 N. Western Avenue | Oklahoma City, OK 76118 | 405-935-8000
AskChesapeake@chk.com | chk.com | NYSE: CHK

Produced Water Reuse and Recycling Challenges and Opportunities Across Major Shale Plays

Matthew E. Mantell, P.E.
Chesapeake Energy Corporation

The statements made during the workshop do not represent the views or opinions of EPA. The claims made by participants have not been verified or endorsed by EPA.

Water Use in Shale Development

Water is an essential component of shale development. Operators use water for drilling, where a mixture of clay and water is used to carry rock cuttings to the surface, as well as to cool and lubricate the drillbit. Drilling a typical Chesapeake shale well requires between 65,000 and 600,000 gallons of water. Water is also used in hydraulic fracturing, where a mixture of water and sand is injected into the shale at high pressure to create small cracks in the rock and allows gas to freely flow to the surface. Hydraulically fracturing a typical Chesapeake shale well requires an average of 5 million gallons of water. The water supply requirements of shale oil and gas development are isolated in that the water needs for each well are limited to drilling and development, and the placement of shale wells are spread over the entire shale play. Subsequent fracturing treatments of wells to re-stimulate production are possible, but unlikely, and re-stimulation is dependent upon the particular characteristics of the producing formation and the spacing of wells within the field. A breakdown of approximate water use for drilling and fracturing by shale play is provided below:

Table 3. Water use in major shale plays

Shale Play	CHK [1] Average Drilling Water Use per Well (in gallons)	CHK [1] Average Hydraulic Fracturing Water Use per Well (in gallons)	Total Average Water Use Per Well *
Gas Shale Plays (primarily dry gas)			
Barnett	250,000	3,800,000	~ 4.0 Million Gallons Per Well
Fayetteville	65,000	4,900,000	~ 4.9 Million Gallons Per Well
Haynesville	600,000	5,000,000	~ 5.6 Million Gallons Per Well
Marcellus	85,000	5,500,000	~ 5.6 Million Gallons Per Well
Liquid Shale Plays (Gas, Oil, Condensate)			
Eagle Ford	125,000	6,000,000	~ 6.1 Million Gallons Per Well
Frontier / Niobrara	300,000	3,000,000	~ 3.3 Million Gallons Per Well

[1] CHK: Chesapeake; Source: * Chesapeake Energy 2010b

Produced Water Management

Produced water plays a key role in the environmental and economic viability of shale oil and gas development. Produced water is a byproduct of all oil and natural gas (energy) development. In order to successfully develop these resources, produced water has to be effectively managed.

For the purposes of this discussion, *produced water* is all water that is returned to the surface through a well borehole and is made up of water injected during the fracture stimulation process, as well as natural formation water. Produced water is typically produced for the lifespan of a well, although quantities may vary significantly by play. Produced water quality can also vary tremendously from brackish (not fresh, but less saline than seawater) to saline (similar salinity to seawater) to brine (which can have salinity levels multiple times higher than seawater). Furthermore, the term *flowback* refers to the *process* of excess fluids and sand returning through the borehole to the surface. For this discussion, the water produced during flowback operations is considered produced water.

The feasibility of produced water reuse is dependent on three major factors. First is the quantity of the produced water generated, including the initial volume of produced water generated (typically during the first few weeks after stimulation). The second factor is the duration in time of produced water generation, including the rate at which water is generated and how it declines over time. Wells that produce significant volumes of produced water during the initial time period are preferred for reuse due to the logistics involved in storing and transporting the water for reuse. A continuous volume can keep tanks and trucks moving, increasing the economic efficiency of reusing the produced water from one wellsite to another. The Barnett, Fayetteville, and Marcellus Shales all produce a significant volume of initial produced water enabling the effectiveness of reuse. These three major shale plays produce approximately 500,000 to 600,000 gallons of water per well in the first 10 days after completion. This volume is sufficient to provide approximately 10% to 15% of the total water needed to fracture a new well (see Table 3 above). The Haynesville Shale produces less water, approximately 250,000 gallons per well in the first 10 days after completion. This is approximately 5% of the total water needed to fracture a new well.

Long-term produced water production is also important because wells that produce large volumes of produced water for long periods of time will require a disposal or reuse option that is located in close proximity to the wellsite in order to retain the economic viability of the operation. The unit of measurement used for comparison of long term produced water is gallons of water per million cubic feet (MMCF) of gas or hydrocarbon liquid equivalent. This unit of measurement for comparing volumes is exclusive to shales because there appears to be a direct correlation between hydrocarbon production and long term produced water generation in the major shale plays. Barnett Shale wells generate by far the largest volume of produced water of any major shale play at greater than 1,000 gallons per MMCF. The Barnett Shale is believed to contain larger volumes of natural formation water present in, and in close proximity to the shale. The Eagle Ford, Haynesville, and Fayetteville Shale are moderate produced water generating plays at approximately 200 to 1,000 gallons per MMCF. These shale formations are relatively desiccated and allow less fluid production per MMCF. The lowest long term produced water volumes come from the Marcellus Shale. The Marcellus is a highly desiccated formation that tends to trap fluids in the shale through physical / chemical interactions. Water production is less than 200 gallons per MMCF in the southern portion of the play in West Virginia, and closer to 25 gallons per MMCF in northern portion of Pennsylvania.

The third major factor in produced water reuse is the quality of the produced water. Total dissolved solids (TDS), also known as the salinity, total suspended solids (TSS), the larger suspended particulates in water, scale-causing compounds (calcium, magnesium, barium, sulfate) and bacteria growth all have a major effect on the feasibility of reusing produced water. TDS can be managed in the reuse process by blending with freshwater to reduce the TDS. Blending is necessary because high TDS can increase friction in the fluid which is problematic in the hydraulic fracturing process. TSS can be managed with relatively inexpensive filtration systems. Filtration of TSS is necessary because elevated solids can cause well plugging and also decreases biocide effectiveness. Scale and bacteria causing compounds can be managed with chemical treatments or advanced filtration, but each additional treatment step reduces the economic efficiency of the process. The ideal produced water for reuse has low TDS, low TSS and little to no scale or bacteria-causing compounds. (Chesapeake Energy 2010d)

Produced Water Management Options

While produced water is generated with the production of oil and gas (energy) as stated above, energy also plays a key role in determining the best way to manage produced water. Most produced water is of very poor quality and may contain very high levels of natural salts and minerals that have dissociated from the target hydrocarbon reservoir.

Two classifications of treatment technologies are available for treatment and reuse of produced water: conventional treatment and advanced treatment technology. Both classifications have energy, environmental, and economic impacts that are directly impacted by produced water quality. Conventional treatment includes flocculation, coagulation, sedimentation, filtration, and lime softening water treatment processes. These treatment processes are generally effective in removing water quality parameters such as suspended solids, oil and grease, hardness compounds, and other nondissolved parameters. These conventional water treatment processes can be energy intensive, but are typically *much less* energy intensive than the salt separation treatments listed below. Conventional processes such as flocculation, coagulation, and lime softening utilize chemicals (sometimes in large volumes) which may have a significant energy input in the development of these chemicals used in the treatment process. However, simple filtration methods with little to no chemical inputs have a much lower energy, environmental, and economic impact.

Advanced treatment technology includes reverse osmosis membranes, thermal distillation, evaporation and/or crystallization processes. These technologies are used to treat dissolved solids, primarily consisting of chlorides and salts, but also including dissolved barium, strontium and some dissolved radionuclides. These dissolved parameters are much more difficult and energy intensive to treat and can only be separated with these advanced membrane and thermal technologies. Treating dissolved solids is a very energy intensive process. These processes are the “second level” or more advanced form of treatment because similar conventional processes listed above are typically needed upfront to ensure that most of the non-dissolved parameters listed above are removed prior to the dissolved solids treatment process.

Outside of treatment for reuse, disposal is the other produced water management option. Outside of the Marcellus Shale, salt water disposal wells are by far the most common method of disposing of produced fluids from shale operations. Surface discharge via wastewater treatment plants has historically been a common treatment technique in the northeast United States, but has been generally phased out due to stricter discharge regulations and natural evolution of the industry due to the Marcellus Shale development. As a note, Chesapeake Energy does not currently discharge any produced water either directly, or via wastewater treatment plants in any shale play.

Energy, environmental and economic considerations must be carefully considered when discussing possible reuse and disposal options for produced water. Much discussion and technology development has focused on treatment technologies that can treat produced water so it is suitable for some form of reuse. These options include reuse in oil and gas operations, municipal, agricultural, and/or industrial operations. Lower dissolved solids produced water (<30,000 ppm TDS) may be feasible for treatment to reuse outside of oil and gas operations. Higher dissolved solid produced waters (> 30,000 ppm TDS) should only be reused where the high salt/salinity content can be kept in solution (to avoid the intense energy input to separate salts). Operators have successfully demonstrated this ability by using conventional treatment processes on high TDS waters, then managing the TDS by blending the fluids in hydraulic fracturing operations. The feasibility of relying on high TDS produced waters for potential municipal or agricultural water supply doesn’t make sense from an energy, economic, or environmental perspective due to the availability of alternative low quality water resources that could be treated to acceptable standards with far lower energy inputs. This includes municipal wastewater, brackish groundwater, and even seawater when logistically feasible. Based on this same logic, environmental and economic benefits may directly correlate when evaluating reuse versus disposal. For example, in areas with extensive salt water disposal well infrastructure like the Barnett Shale, salt water disposal wells are in close proximity to operations, and are a low cost, low energy, safe, and effective alternative to advanced reuse.

The energy requirements needed to treat Barnett Shale produced water (outside of direct filtration and blending) is significant. Since all energy sources result in some form of air emissions, water use, and/or waste generation; reusing produced water in this area using an advanced treatment technology may have greater negative environmental impacts than salt water disposal. Furthermore, oil and gas operations that keep dissolved solids in solution and use the fluid in completion operations for subsequent wells can effectively reduce the volume of fresh water needed for future operations by significant amounts. The onshore shale oil and gas industry has recently been very successful in utilizing conventional, low energy treatment systems to remove suspended solids from produced water and in using this water in hydraulic fracturing operations. From an energy efficiency standpoint, this is a much more efficient use of energy and water than treating produced water to drinking water standards.

Produced Water Reuse and Recycling: The Chesapeake Energy Experience

Over the past three years, Chesapeake has developed and implemented a highly successful produced water reuse program in its Marcellus Shale operating area, and has extended this program to all its shale operating areas. Chesapeake is not alone as many other onshore shale oil and gas companies have also been working to continue to reduce the volume of freshwater utilized in operations and thereby reducing the need to compete with other traditional users of freshwater.

Barnett Shale Reuse

Reuse of produced water in the Barnett Shale is limited by the high volumes of water produced and the corresponding availability of Class II saltwater disposal wells (SWDs) in close proximity to well sites. Barnett Shale produced water generally has higher levels of TDS, low TSS and moderate scaling tendency. Chesapeake is currently treating and reusing approximately 6% of the total water needed to drill and fracture Barnett Shale wells in the southern portion of the play. Currently, logistics and economics are the main limiting factors in preventing higher levels of reuse in this area. These factors (logistics and economics) as well as urban curfew limitations (limited 24 hour operations in urban Ft Worth areas) currently prevent the feasibility of reuse in Chesapeake's northern Barnett Shale operational areas. However, in the northern (urban) portion of the Barnett Shale, Chesapeake is pioneering the use of evaporative technologies that utilize waste heat from gas compressors to reduce the volume of water injected into salt water disposal wells. The benefit of this technology is the prolonged lifespan of the salt water disposal well (heavier concentrated brines may actually be better for disposal wells) and also the ability to manage fluids with fewer disposal wells.

Fayetteville Shale Reuse

Fayetteville Shale produced water is generally of excellent quality for reuse and the volumes of water generated are typically sufficient. Fayetteville Shale produced water has very low TDS, low TSS and low scaling tendency. Chesapeake is currently meeting approximately 6% of drilling and fracturing needs in the Fayetteville Shale with produced water reuse with a target goal of 20% reuse in the play. Since TSS levels are low, very limited treatment (filtration) is needed prior to reuse. As with the Barnett Shale, logistics and economics are currently the main limiting factor in preventing higher levels of reuse in the Fayetteville Shale.

Haynesville Shale Reuse

The Haynesville Shale produces a smaller volume of produced water initially (compared to the other major plays) and has very poor quality produced water. TDS levels are high immediately, TSS is high and the produced water has high scaling tendency. The quality and volume factors combined with an adequate SWD infrastructure make produced water reuse in the Haynesville very challenging. Chesapeake has looked into produced water reuse in the Haynesville, but low produced water volumes, poor produced water quality and the resulting economics have prevented successful reuse of produced water in the Haynesville Shale to date. However, due to the large volumes of higher quality drilling wastewater generated during the drilling process, Chesapeake is actively exploring options to reuse this wastewater in subsequent drilling and fracturing operations.

Marcellus Shale Reuse

In terms of produced water generation, the Marcellus Shale is ideal in that it produces a significant volume of produced water within the first few weeks and then the water production generally falls off very quickly. The quality of Marcellus Shale produced water is good with moderate to high TDS, low TSS and moderate scaling tendency. The TDS is managed with precise blending of produced water with freshwater during a subsequent fracture treatment and the TSS is managed with a simple particle filtration system consisting of a 100-micron filter followed by a 20-micron filter. Scaling and bacteria are managed through a very precise monitoring and testing program to ensure the compatibility of the produced water with the freshwater when blended for use during fracture stimulation.

Chesapeake's Marcellus Shale reuse program has been tremendously successful. In Chesapeake's core operating area of the northern Marcellus in north-central Pennsylvania, Chesapeake is reusing nearly 100% of all produced water and drilling wastewater. This reuse can reduce the volume of freshwater needed to drill and hydraulically fracture subsequent Marcellus Shale wells by 10% to 30%. Resulting benefits include the need for less fresh water for hydraulic fracturing operations (which reduces the impact on local supplies) and also reduces truck traffic on public roads because less fresh water is hauled (resulting in less wear and tear on roads, reduced noise and air quality impacts). From an operational perspective, the reuse program is attractive because it helps reduce the cost of operations including wastewater disposal costs, water supply costs, and transportation costs. Note that only a fraction of the water utilized in the drilling and fracturing process is returned to the surface as produced water (Chesapeake Energy 2010b). Furthermore, Chesapeake has moved to a closed loop synthetic oil based mud system for drilling operations, which significantly reduces wastewater generated from the drilling process.

Criticisms of Shale Gas Water Use: Removal of Water from the Effective Hydrologic Cycle

One of the major criticisms to the use of water in the development of oil and natural gas supplies, particularly in the hydraulic fracturing of shale plays, is the so-called "permanent removal" of water from the surface and near sub-surface (effective) hydrologic cycle. While the focus of this abstract and presentation is on produced water management, it is important to address this criticism about the loss of water as it directly relates to salt water disposal well practices, produced water generation volumes, and shale water management in general. Regardless of the shale play, since the majority of produced water either remains in the formation or is disposed of in another suitable geologic formation (via Class II SWDs), this water is indeed removed from the effective hydrologic cycle. This may lead some to criticize and treat oil and natural gas water use differently than other major water users like power plants who *consume* water during the cooling process. The argument is the power plant type of *consumption* is *evaporation* and the volume of water evaporated is simply released to the atmosphere as water vapor and is still in the effective hydrologic cycle. These concerns about the permanent loss of water from the effective hydrologic cycle can easily be addressed with a simple explanation of natural gas combustion. When natural gas is combusted with oxygen (air) it forms two by-products, carbon dioxide and water vapor. The balanced combustion reaction is shown below:

It is the generation of water vapor that ultimately offsets the removal of water from the effective hydrologic cycle. Based on some common assumptions about natural gas and natural gas combustion, approximately 10,675 gallons of water vapor are produced with the combustion of one MMCF of natural gas. (These calculations are shown in detail along with all assumptions in Appendix A.) This volume of water vapor generation was applied to determine approximately how much natural gas needs to be generated and combusted to offset the volume of water used in the development of a typical shale well in each major shale play. The results are calculated and shown in Table 4 including the average amount of time needed for a typical Chesapeake well to produce the volume of natural gas needed to offset the water used to develop (drill and fracture) the well.

Table 4. Water vapor combustion and hydrologic cycle volume recovery by major shale play

Shale Play	Average Water Use Per Well (in gallons)*	CHK Estimated Average Natural Gas Production Over the Life of Well (in cubic feet **	Cubic Feet of Natural Gas Needed for Combustion to Offset Shale Gas Water Use (Based on 10,675 gal/MMCF Natural Gas Combusted)	Time for an Average CHK Well to Produce Needed Natural Gas to Offset Water Used in Well
Haynesville	5,600,000	6,500,000,000	525,000,000	< 6 Months
Marcellus	5,600,000	5,200,000,000	525,000,000	< 6 Months
Barnett	4,000,000	3,000,000,000	375,000,000	< 6 Months
Fayetteville	4,300,000	2,600,000,000	403,000,000	< 9 Months

Source: *Chesapeake Energy 2010b, **Chesapeake Energy 2010c

As shown above, a well in any of the four major shale plays produces enough natural gas in less than nine months, that when combusted, offsets the entire volume of water used in the development of that well with wells in the Barnett, Marcellus and Haynesville generally producing enough gas in less than six months of production. Please note that these wells are anticipated to produce natural gas for more than 20 years. (Chesapeake Energy 2010b)

Major Conclusions

1. The U.S. Onshore Oil and Natural Gas Industry is reducing the volume of freshwater utilized in operations, thereby reducing the need to compete with other traditional users of freshwater
2. Feasibility of produced water reuse is dependent on three major factors: quantity, duration, and quality of produced water generated

3. Produced water quantity, duration, and quality can all vary considerably between shale plays and can even vary geographically within the same play
4. Environmental and economic benefits may directly correlate when evaluating reuse versus disposal options
5. The volume of water "removed" from the effective hydrologic cycle during hydraulic fracturing OR produced water disposal via salt water disposal wells is more than offset during the combustion of the hydrocarbon fuels produced

Appendix A: Water Vapor from the Combustion of Natural Gas Calculations

Assumptions

- Typical natural gas makeup assumptions:

Methane (CH_4)	**~ 95%**
Ethane (C_2H_6) Propane (C_3H_8) n-Butane (C_4H_{10}) Carbon Dioxide (CO_2) Nitrogen (N)	**~5% combined**
Sulfur (S)	

- Due to variations in natural gas makeup (above), take conservative approach and only use
- methane to calculate water vapor production, although ethane (C_2H_6), propane (C_3H_8) and nbutane
- (C_4H_{10}) when combusted will also produce water vapor.
- Balanced Equation for Methane Combustion: **$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$**
- Assume normal temperature and pressure (68°F and 1 atm)
- Volume of 1 mole of CH_4 at 68°F is 0.0026 lb mole/ft^3
- Molecular weight of water is 18 lb/lb mole
- Liquid water density at 68°F is 8.33 lbs/gallon

Calculations

Step One: Determine how much methane is in one million cubic feet (MMCF) of natural gas:

1. 1,000,000 cu-ft of natural gas x 0.95 (methane component) = 950,000 cu-ft of CH_4

Step Two: Determine the number of pound mol of CH_4 using the assumption above for the volume of one mole of CH_4.

2. 950,000 cu-ft of CH_4 x (0.0026 lb mol CH_4 / ft^3 of CH_4) = 2,470 lb mol CH_4

Step Three: Using the balanced equation above, determine how many pounds of mols of water vapor are produced in the combustion process.

3. 2,470 lb mol CH_4 x (2 lb mol H_2O / 1 lb mol CH_4) = 4,940 lb mol H_2O

Step Four: Using the molecular weight of water, determine how many pounds of water vapor areproduced in the combustion process.

4. 4,940 lb mol H_2O x (18 lb H_2O/1 lb mol H_2O) = 88,920 lb H_2O

Step Five: Using the liquid water density, determine the volume of water vapor produced.

5. 88,920 lb H_2O x (1 gal H_2O/8.33 lb H_2O) = **10,675 gals H_2O (as vapor) per MMCF**

Note: Not all natural gas that is consumed is combusted. According to a 1995 DOE Topical Report on "Economic Evaluation and Market Analysis for Natural Gas Utilization," approximately 3.5% (relatively negligible) of natural gas is used as feedstock for ammonia, methanol, ethylene and hydrogen production.

References

Chesapeake Energy. 2010b. Operational Data.

Chesapeake Energy. 2010c. Investor Presentation. http://www.chk.com/Investors/Pages/Presentation.aspx

Chesapeake Energy. 2010d. Operational Experience.

USDOE, 1995. U.S. Department of Energy: Economic Evaluation and Market Analysis for Natural Gas Utilization – Topical Report – 1995. http://www.osti.gov/bridge/purl.cover.jsp?purl=/211345-iEUh0M/webviewable/