A Day in the Life of a Barrel of Water:
Evaluating Total Life-Cycle Costs of Hydraulic Fracturing Fluids*

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Abstract

For several years now, regulatory agencies including the US Environmental Protection Agency (EPA) and energy associations like the American Petroleum Institute (API) have provided recommendations, regulations and guidelines to improve water management in oil and gas exploration. Energy companies from Apache to Devon and Seneca to Williams have deployed new best-practice methods to reduce fresh water usage in drilling and hydraulic fracturing. To fully appreciate the total life-cycle costs of fluids used for hydraulic fracturing, one needs to examine the total costs of fluid acquisition, management, and disposal. Typically, these costs are divided within various groups within an operator (i.e., completions and production) with emphasis on acquisition during the completions process. This article examines the total hydraulic fracturing fluid-life-cycle costs and examines when fracturing fluids energized with carbon dioxide (CO_2) or nitrogen (N_2) to reduce the volumes of water required can be more economical for hydraulic fracturing. In addition, when the added benefit of energized fluids increasing production performance is included, the unit costs of production can be lower even when total life-cycle costs comparisons are at par or higher. To approach this analysis, we look here at "A Day in the Life of a Barrel of Water" used for hydraulic fracturing.

Selected References

API, 2010, Guidance/Best Practices on Hydraulic Fracturing, HF2 – Water Management Associated with Hydraulic Fracturing, 1st Edition, June 2010.

EPA Hydraulic Fracturing Study Plan, 2011, EPA/600/R-11/122, November 2011.

EPA, 2012, Study of the Potential Impacts of Hydraulic Fracturing on Drinking Water Resources: Progress Report, December 2012.

Center for Energy Economics and Policy, 2012, Managing the Risk of Shale Gas: Identifying a Pathway toward Responsible Development / A Review of Shale Gas Regulations by State, http://www.rff.org/shalegasrisks.

Devon, 2011, API Workshop on Commitment to Excellence in Hydraulic Fracturing October 4th, 2011, Pittsburgh, PA.

Halliburton, Shale Water Management Initiative, 2012, presentation, November 29, 2012.

Linn Energy, 2012, Shale Gas Water Management Initiative 2012 presentation, November 29, 2012.

National Resources Defense Council, 2012, Water Sustainability Study, 2012.

Shell Global Solutions, 2012, Shale Gas Water Management Initiative 2012 presentation, November 29, 2012.

State of Utah Oil and Gas, Division of Oil, Gas, and Mining, 2013, Production data http://oilgas.ogm.utah.gov/index.htm.

Tinker, Rich, 2012, U.S. Drought Monitor: NOAA/NCEP/CPC http://droughtmonitor.unl.edu/ (comparable maps [e.g., http://www1.ncdc.noaa.gov/pub/data/cmb/drought/nadm/nadm-201212.jpg] accessed March 30, 2013)

University of Texas, eFrac well simulation program for energized fluids.

Oil and Gas Services.

A Day in the Life of a Barrel of Water

…Evaluating total life-cycle costs of hydraulic fracturing fluids.

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Content

The Linde Group
Based on two pillars with extensive synergies

The Linde Group

Linde Gas

Linde Engineering

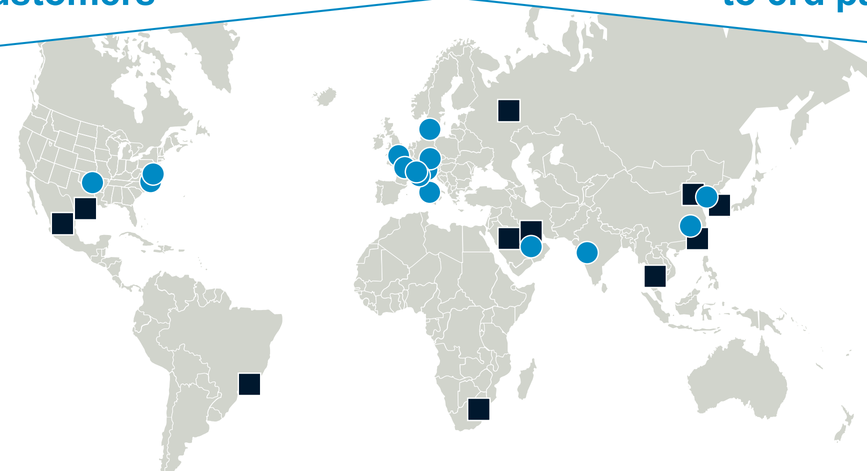
- $18B Revenues & 130 years as cryogenics operating & technology company
- Global network- **60,000** employees in 100 countries

Linde Engineering with leading market position in all segments

Air Separation Plants	Hydrogen & Synthesis Gas Plants	Petrochemical Plants	Natural Gas Plants
			
Worldwide #1	**Worldwide #2**	**Worldwide #2**	**Leading niche supplier**

Production of plants for Linde Gas and 3rd party customers

Providing chemistry and energy related solutions to 3rd party customers



Supporting the energy/environmental mega-trend and leveraging customer relations for gas projects

Gases Division

Wide range of products and services

Gases

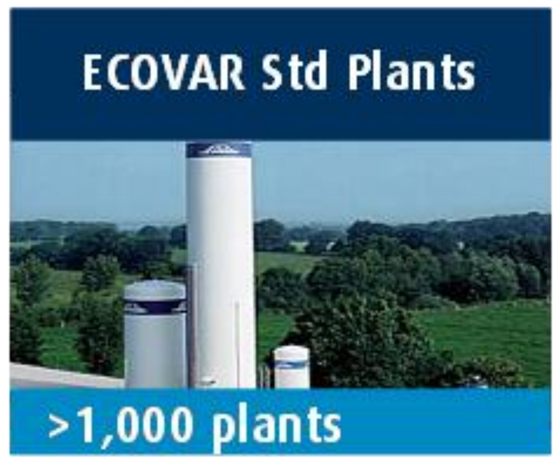
Air Gases	Other Gases	Specialty Gases	Medical Gases
— Nitrogen — Oxygen — Argon — Rare Gases: Krypton, Neon, Xenon	— Acetylene — Helium — Propane — Carbon Dioxide — Carbon Monoxide — Hydrogen	— Pure Gases — Specialty Gas Mixtures	— Medical Oxygen — Nitric Oxide (NO) — Nitrous Oxide (N_2O)

Services

Processes and equipment for use of gases in the most diverse applications

— Chilling, freezing and packaging of food
— Protection and dispensing of beverages
— Heating, melting and treatment of metal
— Welding and cutting in metal fabrication
— Water treatment and environmental protection
— Calibration and testing in laboratories
— Production of chemicals and pharmaceuticals

Engineering and tonnage supply synergy



— 5,500 operating staff

How we deliver in North America

- $2.5 billion in sales in 2011
- 16,000 employees throughout the U.S., Canada and the Caribbean
- 95,000 customers
- Over 400,000 bulk deliveries per year
- Industry leading National Operations Center, Stewartsville, NJ
- Over 400 sales, retail, plant and depot locations
- More than 1,300 delivery vehicles
- The industry’s strongest distributor network

In North America we supply …

… enough oxygen to the steel industry to produce 15 million tons per year of steel and 1.5 million cars

… enough CO_2 to the beverage industry to carbonate 180 billion 12 ounce cans of soda

… enough nitrogen to the food industry to freeze 25 billion chicken nuggets

… enough helium to the medical imaging industry
to operate 3400 MRI machines

… enough oxygen to the healthcare community to sustain life for >1 million patients

With strong focus in key growth areas

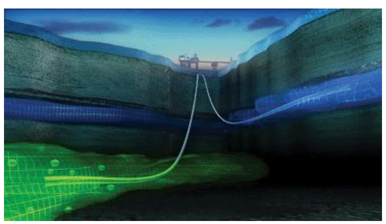
Merchant Liquid Natural Gas (LNG)

- Displace diesel
- CO_2 reduction

Enhanced Oil Recovery (EOR)

- Maturing oil fields
- High oil prices

Carbon Capture & Storage / Usage



- Regulations
- Funding
- Coal reserves

Oil & Gas Services

- Environmental impact
- Productivity

CO_2 Networks

- Increasing need for CO_2 recycling
- Integrated solutions

H_2 as fuel

- Zero emissions
- Drive performance

All are applicable in North America

Linde Gases Division

Innovation
— New application opportunities for our products and services through ongoing R&D — Vast potential of industrial gases still waiting to be unlocked — Solutions for sectors ranging from food processing to welding and the photovoltaic industry — R&D activities focus in particular on the environmental impact of production processes: increase energy efficiency, cut emissions

Life Cycle Costs:
The True Cost of Water

Hydraulic Fracturing Water Usage

— Orders of magnitude greater than drilling

— 2.5 to 5 million gallons *per well*

— 10-70% of hydraulic fracturing wastewater estimated to return (250,000 to 3.5 million gallons)

— Water production tends to increase as well ages (water-to-oil ratios grow from 1:1 to 15:1 as well ages)

Water Management Costs $51 BILLION annually

Life Cycle Costs (simplified)

— Acquisition

— Management

— Disposal

Water Life-Cycle Components

Sourcing	Transport	Storage	Pumping (hydraulic fracturing)	Treatment Flowback Produced	Disposal
Surface water	Trucks	Frac tanks		Centralized treatment facility	Disposal wells
Ground water	Temporary surface lines	Storage ponds		Near-field treatment facilities	
Municipal wastewater	Pipeline	Gathering system		Mobile treatment units	
Industrial wastewater	Rail			No post-treatment	
Recycled water					

IAEE (International Association for Energy Economics), "Water Management Economics in the Development and Production of Shale Resources“, Pac-West Consulting Partners, Q1 2012

Water Management Approach:
Hydraulic Fracturing

US EPA Hydraulic Fracturing Study: Full Life Cycle

Life Cycle includes water acquisition, chemical mixing/site management, well construction, injection/fracturing, flowback and produced water management, and wastewater treatment and disposal.

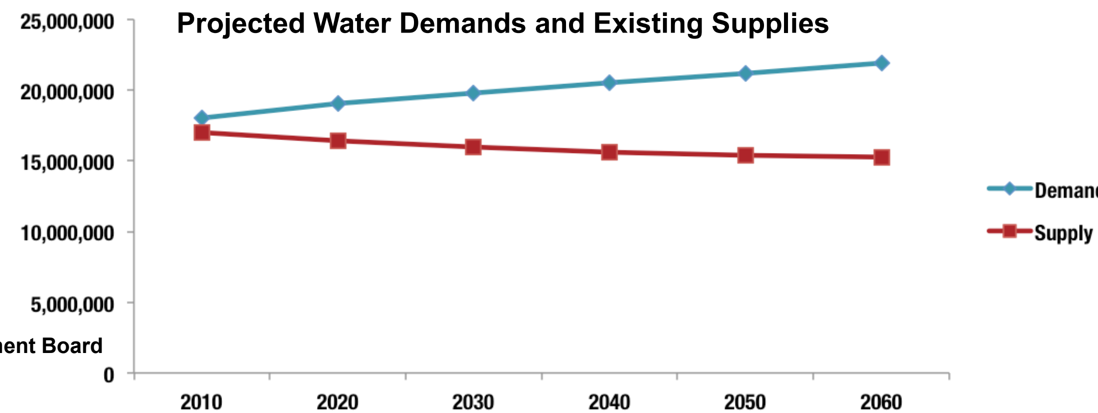
API Water Management Guidance: Best Practices

The purpose of this guidance document is to identify and describe many of the current industry best practices used to minimize environmental and societal impacts associated with the acquisition, use, management, treatment, and disposal of water and other fluids associated with the process of hydraulic fracturing.

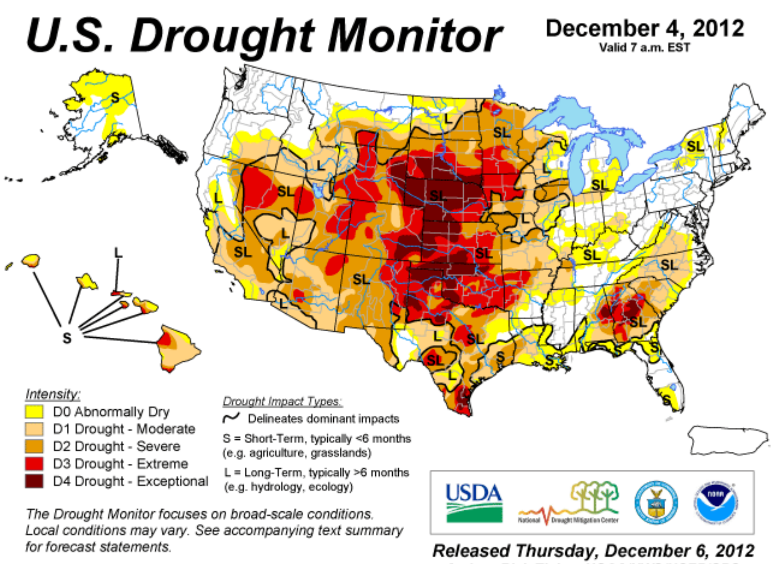
SEAB (Secretary of Energy Advisory Board) Recommendations: Systems Approach

The subcommittee urges adoption of a systems approach to water management based on consistent measurement and public disclosure of the flow and composition of water at every stage of the shale-gas production process.

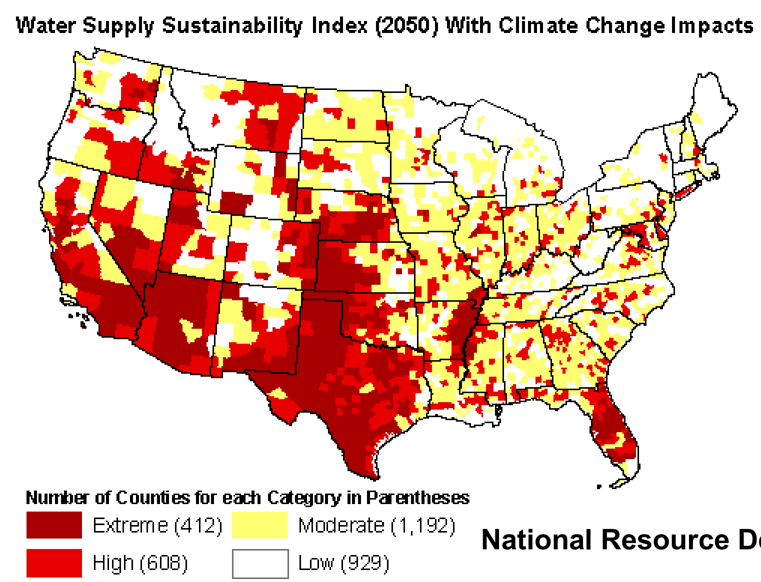
Factors Driving Up Water Costs:
Increasing Demand & Supply Constraints



Water Resource Planning Division, Texas Water Development Board



http://droughtmonitor.unl.edu/



National Resource Defense Council

New study found that more than 1,100 counties -- one-third of all counties in the lower 48 – will face higher risks of water shortages by mid-century. More than 400 of these counties will f extremely high risks of water shortages.

Using Less Water – Energized Fluids:

Lowering Unit Cost of Production

Definition of an energized fluid

— Fracturing fluid that includes at least one compressible, sometimes soluble, gas phase.

Lowering total water usage:

— Displacement of water volume with CO_2 and/or N_2

- **i.e., a 75-Quality foam fracturing fluid contains ~25% water**

— Reduction of total volume of fluid needed for equivalent fracture performance

- **Significant leak-off coefficient reductions as increase quality of CO_2 or N_2**
- **i.e., a 75-quality can mean a leak-off reduction that reduces total fluid volume needs by up to 50%**

— Significant expansion of cold CO_2 as the reservoir heats up; the fluid means less total fluid volume is needed to achieve the same desired effective fracture half-length

Minimizing Hidden Costs – Energized Fluids:
Lowering Unit Cost of Production

Environmental Footprint

— reduction in use of water

— reduced truck traffic resulting in reduced emissions (less water and less proppant)

— reduced dependence on chemicals

Safety

— reduced trips to well site reduces risk of accidents (identified as one of the highest risk)

  — **O&G workers in US are 8.5% more likely to die in motor vehicle accident while on the job than other sectors. Vehicles account for 28% of all worker deaths.***

Lift Size

— less volume of fluid to deal with may reduce size of lift needed

Reduce Dependence on Chemicals

— in particular, for water reuse

Accident Analysis & Prevention Study, 2012.

Proppant Efficacy – Engerized Fluids:
Lowering Unit Cost of Production

Proper proppant placement and minimization of proppant embedment:

— Placement driven by viscosity of fracturing fluid and settling velocity

- **Increasing foam quality increases viscosity without gel residues, leaving self-cleaned proppant pack without fines from overflushing**

— Proppant embedment more problematic in softer rock

- **Embedment factors utilized in fracturing design for slick-water applications can be a width loss of 2 grains of sand equivalent**
- **For a 3-grain effective width design, 5 grains of sand must be utilized – that is a factor of 67% more proppant for a non-energized fluid (adding to the cost)**

Improving Well Productivity – Energized Fluids:
Lowering Unit Cost of Production

Benefits of energized fluids

- Energized fluids expand and gas comes out of solution. – self cleans, reduces leak-off, and in higher temperatures, expands fracture length/width;CO2 offers superior solubility and miscibility properties
- Limits water blocking (unconventionals are undersaturated)
- Reduces clay swelling and fines migration (which lowers conductivity of proppant pack)
- Significantly improves flowback and initial production (especially in dry and depleted formations)

Fracture productivity depends upon:

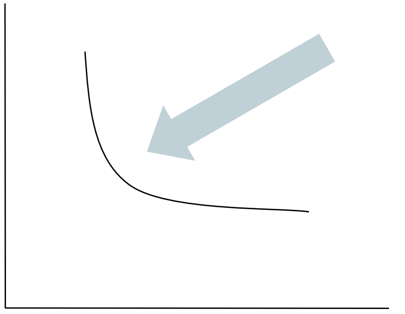
- propped fracture length, which is a function of
  - pumping schedule
  - fluid leak-off
  - proppant transport, which is a combination of
    - fluid/proppant density, fluid viscosity, proppant diameter, and injection rate
- size of the invaded zone, which depends upon:
  - volume of fluid leak-off
  - porosity of the rock formation
- relative permeability to gas (oil) in the invaded zone
- filter-cake damage
- clay swelling
- extent of proppant embedment

Economic Benefits of Energized Solutions:
Lowering Unit Cost of Production

Maximizing the area under the EUR curve

— Unit cost per production most effective economic measure

— Minimizing the slope of the curve has the greatest impact on NPV



Two techniques for looking at economic performance of hydraulic fracturing fluid options

— Simple Calculator Tool

- **for comparing estimated total cost of hydraulic fracturing fluid options**
- **Acquisition, management, disposal calculations**

— Productivity Simulator

- **for comparing estimated productivity factor of hydraulic fracturing fluid options**
- **Hydraulic fracturing simulator designed to fully account for the phase behavior and compositional changes of an energized fluid**

Hydraulic Fracturing Fluid Life Cycle:
Components of Cost – Simplified

Acquisition (Sourcing)

— Surface, fresh, non-potable, municipal, treated, recycled, etc.

— Currently most focused on reducing use of fresh water

— Pre-treatment may be required

Management, Disposal (and Treatment)

— Injection well disposal most common, can also treat or reuse

— With reuse, increase issues with microbial, salinity, and hardness requiring more biocides and polymers

— Management of the flowback and produced water most impacted by volume and time

Transportation

— Typically significant cost component (along with storage and treatment)

— Significant source of emissions (takes ~500 trucks to deliver 3 million gallons water)

— One of the highest safety risk factors is going to and from well site

Significant capital investment often required for achieving best management, sustainable practices

Total Life-Cycle Cost Hydraulic Fracturing Fluids:

Simple Calculator Tool

Acquisition, Management and Disposal – Calculator Input

Water-based fluid		Total barrels
# of stages		
barrels/stage		
Incremental water		bbl
Acquisition		method (source, recycle, reclaim…)
		$/bbl water
		$/ton CO_2
Management		months, flowback
		% flowback (over same months)
		days/month
		# storage tanks
		$/day/storage tank
		hrs setup/tank
		hrs monthly maintenance/tank
		$/hr labor for maintenance & setup
Disposal		method (source, recycle, reclaim…)
		$/bbl

CO_2 Foam Quality		
	0	# of stages
		foam volume improvement factor*
	-	barrels of foam
	-	barrels of water for foam
	5.41	CO_2 bbls/ton
	-	CO_2 tons
	input	
	calculated	can change value manually
	feed	can change value manually

*Use "Quality vs. Leak-off Values" for estimates

*Barrels of foam estimated adjustment based upon leak-off, fluid clean up, imbedment… (if targeting equal fracture volume)

ESTIMATEs

N2 or CO2 Foam Quality	Liquid Leak-off Coeffecient (ft/sqrt(min))*	% Improvement over pure Water
0	0.0034	na
25%		
30%		
40%	0.0023	32%
50%		
55%	0.0021	38%
60%	0.0023	32%
62%	0.0021	38%
65%		
68%	0.0017	50%
70%	0.001	71%
75%	0.0008	76%

*low permeability <1.5mD, pressure drop </= 1000psi

Total Life-Cycle Cost Hydraulic Fracturing Fluids:

Simple Calculator Tool

Acquisition, Management and Disposal – Calculator Output

				Incremental Water	CO_2
	Unit	# Units	Unit Costs	Total costs	Total costs
Acquisition					
Water - Purchase	bbl	-	$	$	
CO_2 - Purchase	ton	-	$		$
Management (post-frac) Storage at Wellhead					
Incremental tanks (24)	mths	-	$	$	NA
Set-up / tank	hrs	-	$	$	NA
Labor monthly	hrs	-	$	$	NA
Disposal					
Injection Wells	bbl	-	$	$	
Total				$	$
Delta cost of water to CO_2				**$**	
Cost/bbl equivalent				Water	CO_2
Acquisition, Management & Disposal				$	$

Example 1: ANADARKO Basin

A Day in the Life of a Barrel of Water – Costs

When you own you own injection well, unit cost of production makes a difference!

-- $10mm capital investment by operator for an injection well to dispose of water and keep disposal cost per barrel low

Estimated Costs, Water vs. CO_2

Fracturing Fluid Cost Comparison - Anadarko, 30 stage well

	Incremental Water	CO_2
Acquisition, Management (post-frac) & Disposal Costs	$ 282,088.00	$1,346,255.00
DELTA cost of water to CO_2	**($1,064,166.00)**	
Cost/bbl Equivalent*	$ 2.77	$ 13.20

*Acquisition, Management & Disposal

Drought conditions and projected water shortages keep pressure on water minimization

Productivity implications…

Example 1: ANADARKO Basin

A Day in the Life of a Barrel of Water – Productivity

Simulated productivity comparison of fracturing fluid alternatives.

Fracture Performance

Fluid Type	Water (eq vol)	CO_2 Foam Quality 40 (eq vol)	40 (75% vol)
L_f (ft)	790	1410	1160
$W_{average}$ (in)	0.1482	0.261	0.2445
k_f (mD)	5000	5000	5000
L_f/L_{re}	0.88	1.32	1.25
F_{cd}	2.63	1.05	1.25
k_d/k	0.1	0.12	0.15
J/J_0	4.5	7.44	7.46
% change over water		65.3%	65.8%

L_f (ft)	fracture ½ length
$W_{average}$ (in)	fracture width, average
k_f (mD)	fracture permeability (INPUT value)
L_f/L_{re}	unitless effective draining radius
F_{cd}	dimensionless fracture conductivity
k_d/k	damaged zone perm/reservoir perm
J/J_0	unitless productivity index

Simulated estimated productivity value for a 30% incremental production gain.

100	BOE/day
30%	incremental production
30	incremental production, BOE/day
$100	$/BOE price
$3,000	incremental production, $/day
$1,095,000	incremental production, annual $
$1,064,166	incremental cost of CO_2 over water
.97	payback years

Example 2: Uinta

A Day in the Life of a Barrel of Water – Costs

When water usage and disposal is difficult and costly, equivalent cost quickly rises and water becomes the more expensive option!

-- Best case scenario

Fracturing Fluid Cost Comparison - Uinta, 8 stage well

	Incremental Water	CO_2
Acquisition, Management (post-frac) & Disposal Costs	$540,217	$562,565
DELTA cost of water to CO_2	**($22,348)**	
Cost/bbl Equivalent*	$14.31	$14.91

*Acquisition, Management & Disposal

-- Recycled water acquisition increases from $5 to $25 per barrel, disposal from $5 to $8/bbl

Acquisition, Management (post-frac) & Disposal Costs	$1,379,913	$562,565
DELTA cost of water to CO_2	**$817,348**	
Cost/bbl Equivalent*	$36.56	$14.91

*Acquisition, Management & Disposal

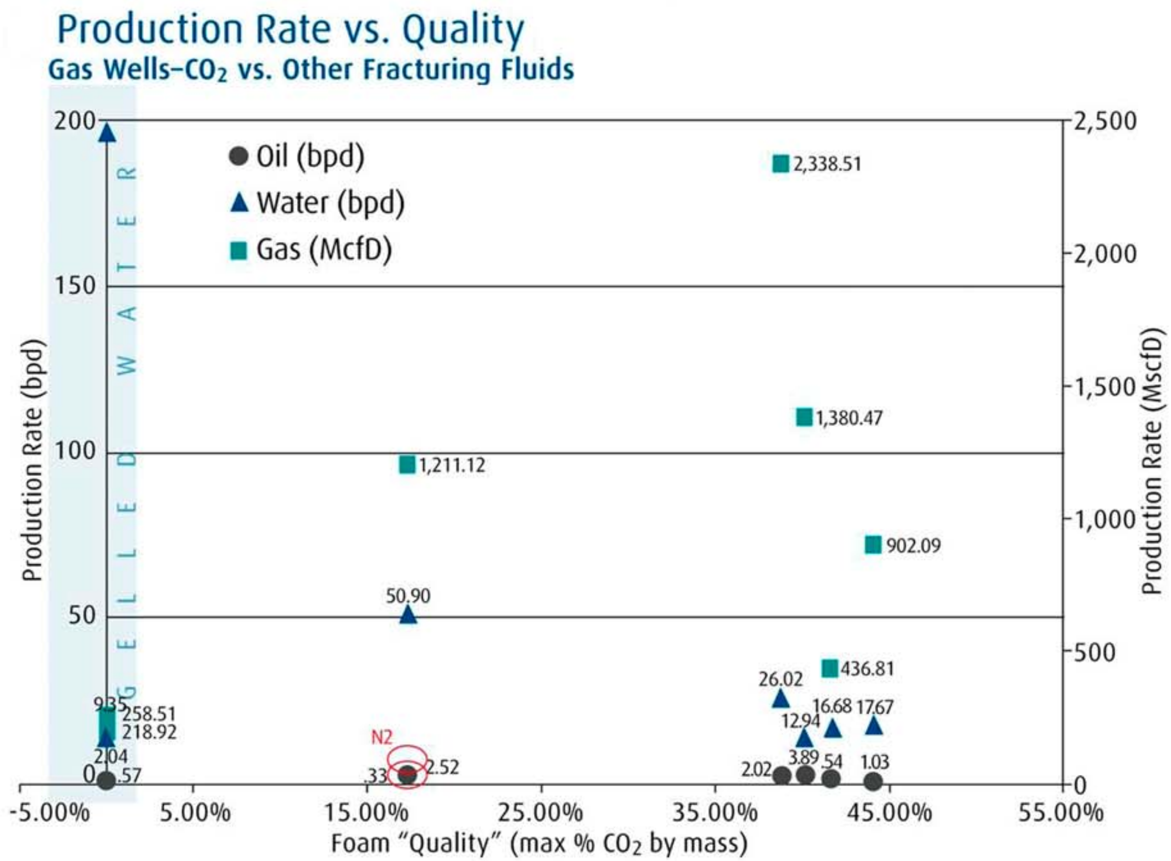
Productivity implications…

Example 2: Uinta

A Day in the Life of a Barrel of Water – Productivity

Average daily production rates for 11 wells during ~7 months of production in 3 county region of Utah.

With no CO_2 or lower quality CO_2, water production was 4.5 to 1.8 times greater than using higher quality CO_2. Gas production was, on average, 5% to 75% higher when using low to higher quality CO_2, compared to water.



Example 3: Marcellus

A Day in the Life of a Barrel of Water – Costs

When disposal costs are high, water can be the most expensive fracturing fluid!

-- disposal at $14.50/bbl

Fracturing Fluid Cost Comparison - Marcellus, 22 stage well

	Incremental Water	CO_2
Acquisition, Management (post-frac) & Disposal Costs	$2,924,212	$2,311,713
DELTA cost of water to CO_2	**$612,498**	
Cost/bbl Equivalent*	$ 15.87	$12.55

*Acquisition, Management & Disposal

-- changing to recycled water as a source drives cost of acquisition up from $3 to $13

Acquisition, Management (post-frac) & Disposal Costs	$4,766,887	$2,311,713
DELTA cost of water to CO_2	**$2,455,174**	
Cost/bbl Equivalent*	$ 25.87	$12.55

*Acquisition, Management & Disposal

Energized Fluids – Recommendations to improve the 3 E's

Economics, EUR, Environment

In well designed hydraulic fracturing processes, energized solutions utilizing CO_2 or N_2 can reduce costs (such as clean-up and disposal) and improve well performance to achieve a lower unit cost of production.

Evaluating the total life cycle of water used in well completions and production is paramount to understanding its true costs.

If full life-cycle cost of water is $5-10/bbl, suggest looking at energized fluids to:

- reduce total costs
- improve well productivity (lowering unit cost of production)
- reduce environmental footprint via water and emissions reduction

References

US EPA, Sudy of the Potential Impacts of Hydraulic Fracturing on Drinking Water Resources: Progress Report, December 2012.

National Resources Defense Council, Water Sustainability Study, 2012.

EPA Hydraulic Fracturing Study Plan, EPA/600/R-11/122, November 2011.

Halliburton, Shale Water Management Initiative 2012 presentation, November 29, 2012.

API, Guidance/Best Practices on Hydraulic Fracturing, HF2 – Water Management Associated with Hydraulic Fracturing, 1st Edition, June 2010

Devon, API Workshop on Commitment to Excellence in Hydraulic Fracturing October 4th, 2011, Pittsburgh, PA

Managing the Risk of Shale Gas: Identifying a Pathway toward Responsible Development, A Review of Shale Gas Regulations by State, Center for Energy Economics and Policy, www.rff.org/shalegasrisks.

Linn Energy, Shale Gas Water Management Initiative 2012 presentation, November 29, 2012.

Shell Global Solutions, Shale Gas Water Management Initiative 2012 presentation, November 29, 2012.

University of Texas, eFrac well simulation program for energized fluids

Production data from State of Utah Oil and Gas, Division of Oil, Gas, and Mining, http://oilgas.ogm.utah.gov/index.htm; Completions data from FracFocus.org.

Thanks for your attention.