Deep Shale Natural Gas:
Abundant, Affordable, and Surprisingly Water Efficient

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This paper was prepared for presentation at the 2009 GWPC Water/Energy Sustainability Symposium held in Salt Lake City, Utah, USA, 13-16 September 2009.

Biographical Sketch of Author

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Abstract

Water is essential to energy resource development; conversely, energy resources are needed for developing, processing, and distributing water resources. As a result, water and energy are interdependent. This "balance" or "nexus" between resources is a critical, yet often overlooked component in evaluating energy resources. Recent technological advancements in horizontal drilling and hydraulic fracturing have unlocked an abundance of deep shale natural gas in the United States. This paper discusses the water efficiency of deep shale natural gas compared to other energy resources. Comparisons will be made by breaking down energy resource efficiency into common units such as gallons of water used per British thermal unit (BTU) of energy produced, gallons of water per megawatt (MW) of electricity produced, and gallons of water per mile driven. Energy resource water use comparisons will be evaluated based on extraction and processing of raw materials into useable fuel sources. Furthermore, comparisons will also be evaluated on power generation water use requirements. Finally, this information will be used to discuss the water efficiency of transportation fuels including plug-in (electrical) hybrids, traditional fuels (gasoline and diesel), biofuels, and compressed natural gas (CNG).

Introduction

Water is essential to energy resource development; conversely, energy resources are needed for developing, processing, and distributing water resources. As a result, water and energy are interdependent. This "balance" or "nexus" between resources is a critical, yet often overlooked component in evaluating energy resources. For example, improving water use efficiency reduces the need to develop, transport, pump, treat, and distribute water resources thereby reducing the amount of power or energy required for these processes. Alternatively, improving energy efficiency reduces demand on electricity generation and transportation fuel consumption, which reduces the need for water resources for power generation cooling and fuel processing, along with reducing the water resources needed to extract the original fuel sources. Overall, improving the efficiency of both water and energy use can help reduce cultural, environmental, and economic impacts / costs of both critical resources.

Recent technological advancements in horizontal drilling and hydraulic fracturing have unlocked an abundance of deep shale natural gas in the United States. Deep shale natural gas development is increasingly scrutinized due to relatively "large" volumes of water required to hydraulically fracture each deep shale natural gas well. This paper will look specifically at deep shale natural gas with a focus on the four "major" United States deep shale gas "plays" and compare the water efficiency of deep shale natural gas to other energy resources. (A "play" is defined as "a set of discovered or undiscovered oil and gas accumulations or prospects that exhibit nearly identical geological characteristics, (USGS 2009)).

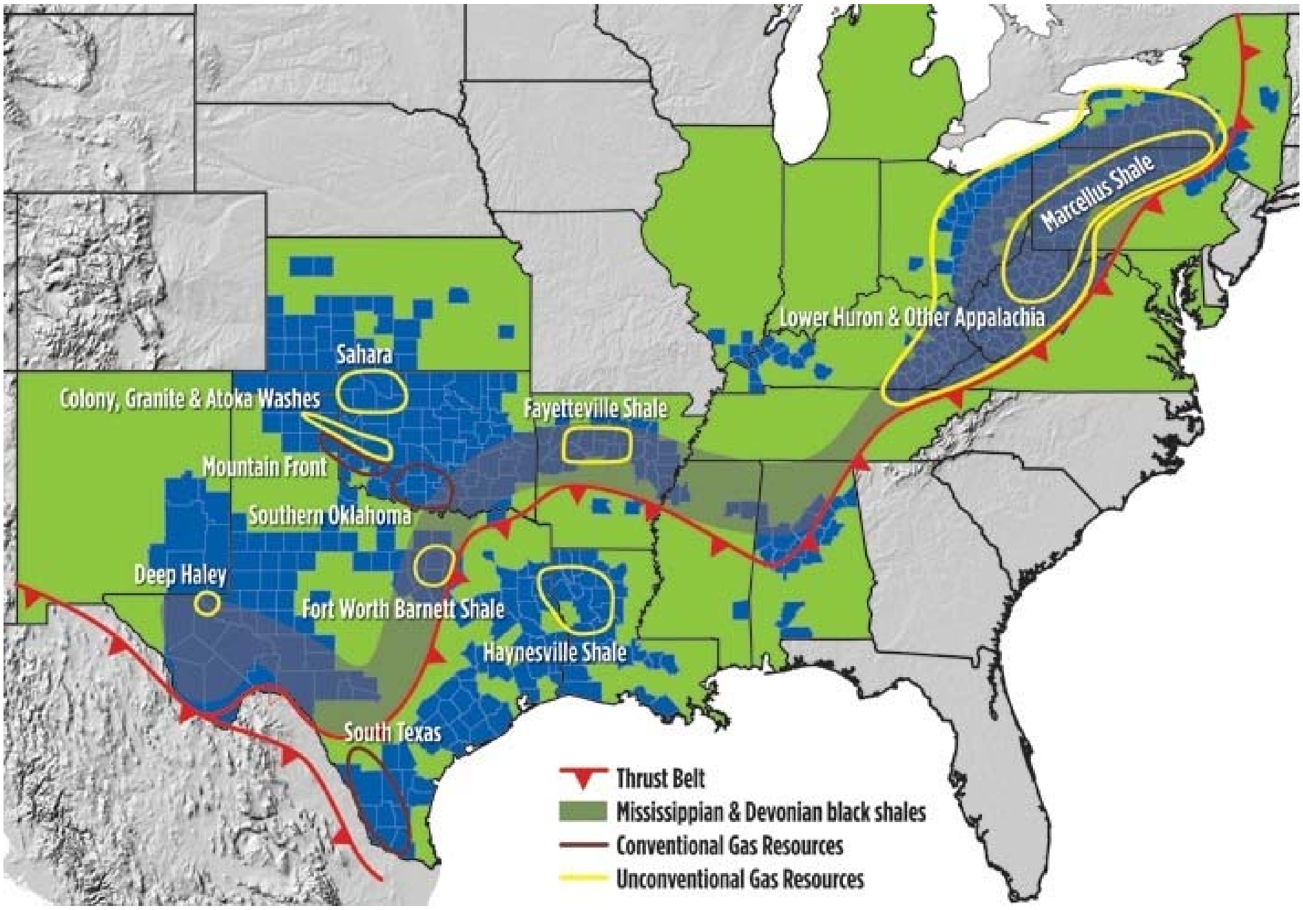
The first water use comparison section will evaluate raw fuel sources based on extraction and processing of raw materials into useable fuel sources. Comparisons will be made by breaking down energy resource efficiency into common units of gallons of water used per British thermal unit (BTU) of energy produced. The second water use comparison will evaluate power generation water use requirements based on power plant type. Comparisons of power generation will be made by converting water use efficiency into common units of gallons of water used per megawatt (MW) of electricity produced. The final water use comparison section will be used to compare the water efficiency of transportation fuels including plug-in (electrical) hybrids, traditional fuels (gasoline and diesel), biofuels, and compressed natural gas (CNG). Comparisons of transportation fuels will be made by converting water use efficiency into commons units of gallons of water used per hundred miles driven.

Deep Shale Natural Gas: Abundant and Affordable

Vast new natural gas resources are being discovered every year across North America. Natural gas drilling activity is at 25-year highs and supplies are rapidly growing (USDOE 2008a). According to recent estimates, at least a 90-year supply is present in the United States (Colorado School of Mines 2009). Meanwhile, the U.S. imports almost 60% of the oil used annually (USDOE 2008b). This creates a financial burden for the U.S., as the oil import bill will likely exceed $500 billion this year, and leaves the U.S. vulnerable to economic and political disruption. Natural gas offers an alternative to U.S. oil imports – approximately 98% of the natural gas Americans currently use comes from the U.S. and Canada (USDOE 2008b, 2008c, 2008d).

One major source of these "vast new natural gas resources" comes from the development of deep shale natural gas formations. Deep shale natural gas is typically found thousands of feet below the earth's surface in tight, low permeability shale formations. Experts have known for years that natural gas deposits existed in deep shale formations, but until recently the vast quantities of natural gas in these formations were thought to be unrecoverable. Today, through the use of a technique called "hydraulic fracturing", combined with sophisticated horizontal drilling techniques, extraordinary amounts of natural gas from deep shale formations across the United States are being safely produced (Fig 1).

Figure 1. Shale gas plays, including the Barnett Shale, the Haynesville Shale, the Fayetteville Shale and the Marcellus Shale *(Chesapeake Energy, 2008a)*



Natural gas production plays a key role in resource sustainability. Consumption of natural gas results in less carbon dioxide emissions, and no mercury or particulate emissions, compared to dominant fuels such as gasoline and diesel (USDOE 1998). Natural gas emits half of the carbon dioxide of coal when used for power generation, and as a vehicle fuel, natural gas emits 30% less carbon dioxide than gasoline (USDOE 1998, 2008e).

Along with being abundant and affordable, natural gas is the most diversely used fuel source available today. Once extracted and processed (requires only minimal processing), natural gas can be used in clean burning power plants, directly and efficiently in residences, to power industrial processes, and in manufacturing of everyday products. On top of these numerous uses, natural gas can also be compressed or liquefied and used as a transportation fuel in heavy-duty tractor trailer trucks, motorcycles, boats, ships, and of course everyday light duty vehicles. No other currently available fuel source can be utilized in so many ways.

Water Use in Deep Shale Natural Gas Development: The Chesapeake Energy Experience

"Hydraulic fracturing" is a technique used in oil and natural gas production to stimulate the production of hydrocarbons. After a well is drilled into reservoir rock that contains oil, natural gas, and water, every effort is made to maximize the production of oil and gas. In hydraulic fracturing, a fluid (usually water containing special high-viscosity fluid additives) is injected under high pressure. The pressure exceeds the rock strength and the fluid opens or enlarges fractures in the rock. These larger, man-made fractures start at the well and extend deep into the reservoir rock. After the formation is fractured, a "propping agent" (usually sand carried by the high-viscosity additives) is pumped into the fractures to keep them from closing when the pumping pressure is released. This allows the oil or natural gas to move more freely from the rock pores to a production well so that it can be brought to the surface (USEPA 2009). The process was first used in commercial oil and gas operations in 1949. Since then the knowledge base has improved, and so have the techniques.

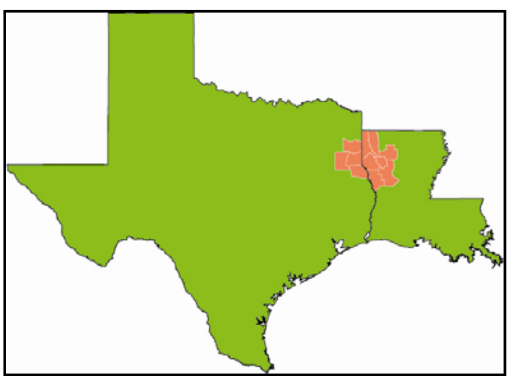
Water is an essential component of deep shale natural gas development. Operators use water for drilling, where a mixture of clay and water is used to carry rock cuttings to the surface as well as to cool and lubricate the drillbit. Drilling a typical Chesapeake deep shale natural gas well requires between 65,000 and one million gallons of water. Water is also used in hydraulic fracturing, where a mixture of water and sand is injected into the deep 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 deep shale natural gas well requires an average of 3.5 million gallons of water.

The water supply requirements of deep shale natural gas development are isolated in that the water needs for each shale gas well are limited to drilling and development, and the placement of shale gas wells are spread out over the entire shale gas play. In other words, these shale gas wells are not drawing water from one single source. Subsequent hydrofrac treatments of wells to re-stimulate production may be applied, though their use is dependent upon the particular characteristics of the producing formation and the spacing of wells within the field.

The Haynesville Shale

The Haynesville Shale extends into northwest Louisiana and east Texas (Fig 2); the exact extent of this play is yet to be determined. Estimated reserves for the Haynesville Shale are 250 trillion cubic feet (TCF) (Chesapeake Energy 2008b). Based on a natural gas price of $8 per thousand cubic feet (MCF), this estimated reserve has a total economic value of $2 trillion dollars. Assuming that US natural gas consumption remains consistent with 2007 use (23 TCF per year (USDOE 2008f)), the Haynesville could supply the United States with all natural gas needs for approximately 11 years.

Figure 2. Texas and Louisiana counties associated with the Haynesville Shale *(Chesapeake Energy 2009a)*

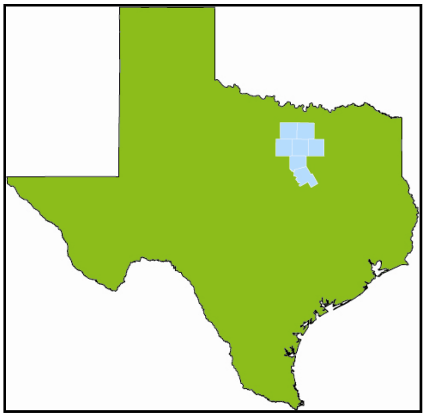


A typical Chesapeake Haynesville horizontal deep shale natural gas well requires an average of one million gallons for drilling, and three million gallons for hydraulic fracturing, resulting in a total water demand per well of approximately four million gallons.

The Barnett Shale

The Barnett Shale of the Fort Worth Basin (Fig 3) is considered a top natural gas play and one of the most effective locations for well development using the latest drilling and completions technologies. Estimates of the amount of natural gas in the Barnett Shale total 30 TCF (USGS 2004), for an economic value of $240 billion dollars, based on assumptions stated above. 30 TCF is enough natural gas to supply the U.S. with all natural gas needs for 16 months. Ongoing exploration and advances in recovery methods are likely to further increase the estimated reserve.

Figure 3. Texas counties with active gas production wells in the Barnett Shale *(Chesapeake Energy 2009a)*

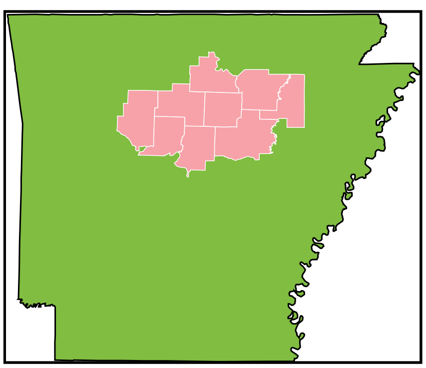


A typical Chesapeake Barnett horizontal deep shale natural gas well requires an average of 400,000 gallons for drilling, and three million gallons for hydraulic fracturing, resulting in an total water demand per well of approximately 3.4 million gallons.

The Fayetteville Shale

The Fayetteville Shale is located in the north-central section of Arkansas (Fig 4). The Fayetteville Shale has a reported 20 TCF of proven natural gas reserves (Oilshalegas 2009). At the natural gas price and consumption rate assumed above, this reserve has an economic value of $160 billion and could supply the US with all natural gas needs for 10 months.

Figure 4. Arkansas counties associated with the Fayetteville Shale *(Chesapeake Energy 2009a)*

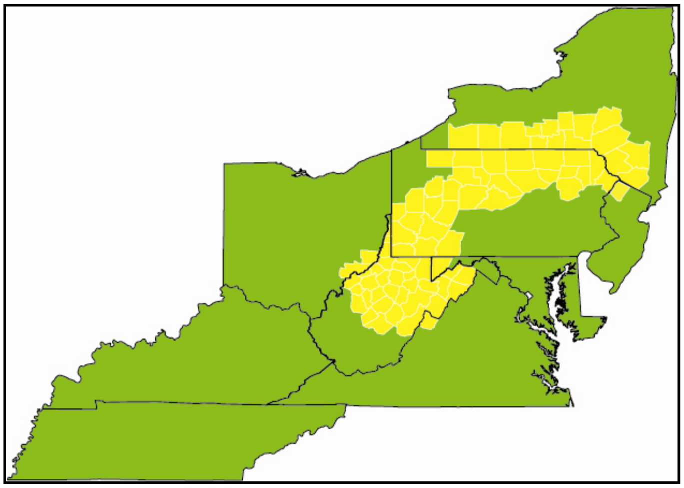


A typical Chesapeake Fayetteville horizontal deep shale natural gas well requires an average of 65,000 gallons for drilling (lower than other shale plays due to the use of air drilling techniques), and four million gallons for hydraulic fracturing, resulting in an total water demand per well of approximately 4.065 million gallons.

The Marcellus Shale

The Marcellus Shale extends across New York, Pennsylvania, West Virginia, and minor portions of Ohio, Virginia, and Maryland (Fig 5). There is an estimated 50 TCF of recoverable natural gas in the Marcellus Shale Play (Engelder 2008), with up to 500 TCF believed to be available. The total economic value of the recoverable reserve is $400 billion dollars, and could supply the US with all natural gas needs for over 2 years.

Figure 5. Counties associated with the Marcellus Shale *(Chesapeake Energy 2009a)*



A typical Chesapeake Marcellus horizontal deep shale natural gas well requires an average of 100,000 gallons for drilling (lower than other shale plays due to the use of air drilling techniques), and four million gallons for hydraulic fracturing, resulting in a total water demand per well of approximately 4.1 million gallons.

Raw Fuel Water Efficiency Comparison

For the purposes of this section, water efficiencies of raw fuels will be reported in terms of gallons of water used per million British Thermal Units (MMBTU) of energy. In this report, "BTU" is used to describe energy content (as opposed to "BTU per hour" which is commonly used to describe the *rate* of energy use by heating and cooling systems).

Natural gas production is commonly reported in volumetric units of "cubic feet" of gas. According to the U.S. Department of Energy (USDOE 2007), one cubic feet of dry natural gas contains approximately 1,028 BTU of energy. This conversion is utilized in the table below to determine the water efficiency of deep shale natural gas in the four major deep shale natural gas plays.

Table 1. Water Use Efficiency of Four Major Chesapeake Deep Shale Natural Gas Plays

Shale Play	Average Water Use Per Well (in gallons) *	CHK Estimated Average Natural Gas Production Over Life of Well (in cubic feet) **	Natural Gas Production Per Well (in MMBTU) based on Conversion of 1,028 BTU per Cubic Feet ***	Water Use Efficiency (in gallons per MMBTU)
Fayetteville	4,065,000	2,200,000,000	2,261,600	1.80
Barnett	3,400,000	2,650,000,000	2,724,200	1.25
Marcellus	4,100,000	3,750,000,000	3,855,000	1.06
Haynesville	4,000,000	6,500,000,000	6,682,000	0.60

*Source: *Chesapeake Energy 2009b, **Chesapeake Energy 2009c, ***USDOE 2007*

Note that the table shows substantial variation by shale play of estimated average natural gas production over the life of a well. The high production volume out of deep shale natural gas wells sets them apart from other natural gas wells including coal bed methane and conventional wells. From a water use perspective, it is this high production that helps offset the larger volumes of water (3-4 million gallons) used in the stimulation (hydraulic fracturing) process during well development.

Outside of wind and solar, natural gas (including deep shale natural gas) is the most water efficient raw fuel source. Table 2 below provides a comparison of "Raw Fuel Source Water Use Efficiency" which includes all water requirements for mining / extracting / growing the raw fuel source and refining / processing the fuel to convert into a useable energy source by a power plant.

Table 2. Raw Fuel Source Water Use Efficiency

Energy Resource	Range of Gallons of Water Used per MMBTU of Energy Produced	Data Source
CHK Deep Shale Natural Gas *	0.60 – 1.80	Includes: Drilling, Hydraulic Fracturing Source: Chesapeake Energy 2009b
Natural Gas	1 – 3	Includes: Drilling, Processing; Source: USDOE 2006, p 59
Coal (no slurry transport) (with slurry transport)	2 – 8 13 – 32	Includes: Mining, Washing, and Slurry Transport as indicated. Source: USDOE 2006, p 53-55
Nuclear (processed Uranium ready to use in plant)	8 – 14	Includes: Uranium Mining and Processing Source: USDOE 2006, p 56
Conventional Oil	8 – 20	Includes: Extraction, Production, and Refining Source: USDOE 2006, p 57-59
Synfuel - Coal Gasification	11 – 26	Includes: Coal Mining, Washing, and Processing to Synthetic Gas. Source: USDOE 2006, p 60
Oil Shale Petroleum	22 – 56	Includes: Extraction / Production, and Refining Source: USDOE 2006, p 57-59
Tar Sands (Oil Sands) Petroleum	27 – 68	Includes: Extraction / Production, and Refining Source: USDOE 2006, p 57-59
Synfuel - Fisher Tropsch (Coal)	41 – 60	Includes: Coal Mining, Washing, Coal to Gas to Liquid Conversion Processing. Source USDOE 2006, p 60
Enhanced Oil Recovery (EOR)	21 – 2,500	Includes: EOR Extraction / Production, and Refining Source: USDOE 2006, p 57-59
Fuel Ethanol (from irrigated corn)	2,510 – 29,100	Includes: Feedstock Growth and Processing Source: USDOE 2006, p 61
Biodiesel (from irrigated soy)	14,000 – 75,000	Includes: Feedstock Growth and Processing Source: USDOE 2006, p 62

**Does not include processing which can add from 0 - 2 Gal per MMBTU*

Geography plays an important role in determining fuel source water efficiency. For simplicity, the values in Table 2 (above) are location independent and transportation water demands are not accounted for. However, if transportation water use was factored in, locally produced fuels would become more water efficient (actual increase in efficiency would depend on the distance from extraction and production to the location of end use). This makes imported fuels such as foreign oil, Alaskan oil and gas, and even off-shore oil and gas, less water efficient depending on location of origin versus location of end use.

Solar and wind sources are not included in the table above because they require virtually no water use for processing (they can be directly captured and used). As a result, these energy sources are the most water efficient. However, in 2008, wind only accounted for 1/2 of one-percent and solar only 1/10th of one percent of all energy consumed in the United States (USDOE 2009). As a result, neither wind nor solar resources can currently be relied upon as a substantial or "baseload level" energy supply.

The extraction and processing of coal as a raw fuel source is relatively water efficient. Water is used in coal cutting (underground mines), for dust suppression (during mining and hauling), and for reclamation and re-vegetation of surface mines. Water requirements for coal can also increase significantly if coal is transported as a slurry through a pipeline. Due to the significant water requirements for slurry transport, these values are included above in Table 2.

Uranium (nuclear) and conventional oil are in the mid-range of fuel sources when comparing water use efficiencies. Water is used in uranium processing for mining, milling, enrichment, and fuel fabrication processes. Even though the extraction processes for conventional oil is similar to that for natural gas (drilling, etc), conventional oil requires refining which uses a significant amount of water for processing.

As a general rule, unconventional oil and synthetic coal extraction and production processes are more water intensive than their conventional counterparts. Enhanced Oil Recovery (EOR) uses relatively large amounts of water due to the waterfloods used to force the oil out of the reservoir. Oil shale and tar sands (oil sands) also use significantly higher amounts of water due to the in-situ steam extraction process and the additional water used to process the liquid petroleum fuel. Synthetic coal (both coal gasification and Fisher-Tropsch coal to liquid) use larger volumes of water due to the conversion process of coal to gas and on to liquid fuel.

As shown in Table 2, the most water inefficient fuel sources are irrigated biofuels including ethanol and biodiesel. Irrigation of the biofuel feedstock requires significant volumes of water input per unit of energy that can be derived from the crop. Biofuels also require a significant amount of water to process the raw fuel into a useable energy source. Water use efficiencies could be improved to a level similar to synthetic coal if only non-irrigated feedstock was used in energy development, although this would significantly decrease the amount of feedstock available due to the limited locations where non-irrigated growth is possible.

Power Generation Water Efficiency

Water is a critical element in power generation. Water is used directly in power generation in hydroelectric power plants, and is more commonly used indirectly as a cooling mechanism in thermoelectric power plants. "Thermoelectric power plants – comprised of power plants that use heat to generate power, such as nuclear, coal, natural gas, solar thermal or biomass fuels – are the single largest water user in the United States" (Stillwell et al. 2009) (note the reference to "largest water user" is based on water "withdrawals" as defined on the following page). Furthermore, thermoelectric and hydroelectric power generation account for the majority of all electricity generation in the United States. As a result, thermoelectric and hydroelectric power plants will be evaluated in more detail in this report than "non-baseload level" sources such as wind turbines and photovoltaic solar panels.

According to the First Law of Thermodynamics, energy can be transformed from one form to another, but it can neither be created nor destroyed. This is the case on power generation for electricity, except power plants by their own nature are very inefficient. In fact, almost all thermoelectric (natural gas, coal, biomass, syngas, and nuclear) power plants are all less than 50% efficient. Even renewable sources like wind turbines are only about 50% efficient, with solar power (concentrated solar and photovoltaics) at a mere 15% efficient. Due to these inefficiencies, thermoelectric power plants must transmit the remaining "wasted energy" in the form of "waste-heat". Waste-heat is either transmitted to flue gases (carbon dioxide, sulfur dioxide, nitrogen oxide, etc) or transferred to cooling water (causing water to heat and/or evaporate). A breakdown of different power plant types and plant efficiencies is shown in the table below. (Stillwell et al. 2009)

Table 3. Typical Efficiencies of Thermoelectric Power Plants

Power Plant Type	Energy Transferred to Electricity (Efficiency)	Energy Transferred to Cooling Water (as Waste-Heat)	Energy Transferred to Flue Gases (as Waste-Heat)	Notes
Natural Gas Combined Cycle (NGCC)	50%	36%	14%	Natural gas directly combusted, exhaust gas (waste-heat) used to produce steam as part of combined cycle
Integrated Gasification (SynGas) Combined Cycle (IGCC)	50%	35%	15%	Coal not directly combusted, coal "gas" combustion drives turbine, and exhaust gas (waste-heat) used to produce steam in combined cycle
Coal / Biomass Steam Turbine	33%	33%	33%	Coal / Biomass combusted to produce steam. Combustion temperature ~ 1,500 °C
Nuclear Steam Turbine *	33%	67%	--	Nuclear reactor used to produce steam. Combustion temperatures ~ 300 °C
Concentrating Solar **	15%	33%	--	Solar power is concentrated and used to produce steam (different than photovoltaic "cells")

**Emission Free*
***Remaining 52% remains as "unconverted solar energy"*
Source: Adapted from Stillwell et al. 2009

Thermoelectric power plants combust a raw fuel source (natural gas, syngas, coal, biomass, and nuclear) to heat water to create steam. The steam turns a turbine on a generator to produce electricity. Once the steam / water is used it is either cooled and recycled back through the plant to be used again (closed-loop cooling), or is discharged into receiving water body (open-loop cooling).

There are advantages and disadvantages to each of the different types of power plant cooling systems. In order to understand these differences, the terms "water withdrawal" and "water consumption" as used in this paper are defined below:

<u>Water Withdrawal</u> -- surface or ground water physically removed from a source for use in a power plant

<u>Water Consumption</u> -- surface or ground water "lost" in the power generating process due to evaporation (no discharge)

Open-loop cooling systems require very large water withdrawals (and large water intake structures) for cooling because the water is only passed through the system one time before it is discharged back into a receiving stream or cooling pond. The main advantage is the actual water consumption is low and due to the single pass of water through the system, these power plants can use lower quality (higher salinity) water. However, disadvantages include potentially severe environmental impacts due to the discharge of water with high temperatures (referred to as "thermal pollution"), and damage to aquatic ecosystems due to the large intake requirements. Due to the environmental impacts of "thermal pollution" many states have environmental rules that regulate the maximum temperature that power plants can discharge into a receiving water body. (Stillwell et al. 2009)

Closed-loop cooling systems typically utilize cooling towers to re-cycle water and dissipate heat by evaporation. The major advantage of closed-loop systems is the lower water withdrawal requirements and limited aquatic system environmental impact. Disadvantages to closed-loop systems include higher water consumption (due to the evaporative cooling process) and the corresponding concentration of pollutants in the cooling water. Due to this "concentrating" effect, the quality of water used in a closed-loop cooling power plant must be of high quality. (Stillwell et al. 2009)

The third and least common type of cooling systems are air cooling systems that require no water to operate. Air cooling is used to a very limited extent due to the high power requirements needed to run the cooling fans, lower overall cooling efficiency, and corresponding increased air emissions per unit of useful power produced due to higher auxiliary power requirements. Because of the limited use of air cooling systems, only open-loop and closed-loop cooling systems are evaluated below.

Table 4. Open-loop Cooling Power Generation Water Use Efficiency

Power Plant Type	Average Gallons of Water Consumed in Power Plant per MWh of Electricity Produced	Average Gallons of Water Withdrawal in Power Plant per MWh of Electricity Produced
Natural Gas Combined Cycle (NGCC)	110	13,760
Coal / Biomass Steam Turbine	280	35,030
Nuclear Steam Turbine	430	42,530

Source: Adapted from Hightower 2008

Three different power plant types utilizing open-loop cooling systems are compared in Table 4 (above). Typically, IGCC (SynGas from coal), concentrating solar, and geothermal steam power plants do not utilize open-loop cooling systems. Of the three power plant types that utilize open-loop cooling, NGCC power plants are the most efficient consuming less than half as much water as a coal/biomass power plant, and approximately one-fourth of the water needed in a nuclear power plant. The corresponding water withdrawal for the NGCC power plant is also significantly less than the coal/biomass plant and the nuclear power plant.

Table 5. Closed-loop Cooling Power Generation Water Use Efficiency

Power Plant Type	Average Gallons of Water Consumed in Power Plant per MWh of Electricity Produced	Average Gallons of Water Withdrawal in Power Plant per MWh of Electricity Produced	Data Source
Natural Gas Combined Cycle (NGCC)	190	240	Sandia Nat'l Labs (Hightower 2008)
Integrated Gasification (SynGas from Coal), Combined Cycle (IGCC)	330	350	Sandia Nat'l Labs (Hightower 2008)
Coal / Biomass Steam Turbine	420	480	Sandia Nat'l Labs (Hightower 2008)
Concentrating Solar	750	760	Sandia Nat'l Labs (Hightower 2008)
Nuclear Steam Turbine	590	830	Sandia Nat'l Labs (Hightower 2008)
Geothermal Steam	1,400	2,050	Sandia Nat'l Labs (Hightower 2008)
Hydroelectric	4,500*	N/A	Dept of Energy (DOE 2006, p 68)

**Due to direct evaporation from holding reservoir*
Note: Wind turbines, photovoltaic solar panels, and direct combustion natural gas turbines (non-combined cycle) have negligible water demands

A comparison of closed-loop cooling power generation water use efficiency in Table 5 above shows significantly lower water withdrawal requirements (advantage) but higher water consumption requirements (disadvantage) when compared to open-loop cooling systems. Once again, when comparing water consumption and water withdrawal requirements based on power plant types, NGCC power plants are the most water efficient. (Note that wind turbines, photovoltaic solar panels, and direct combustion natural gas turbines have negligible water requirements, but due to their limited use, are not included in this evaluation.)

Compared to a NGCC power plant, the following power plants consume significantly higher amounts of water per equivalent amount of electricity produced (expressed as a percentage):

- IGCC (SynGas from coal) power plant → 170% more,
- Coal/biomass plant → 220% more,
- Nuclear plant → 310% more,
- Concentrating solar plant → 390% more,
- Geothermal steam plant → 740% more.

Furthermore, the least water efficient power plant is actually a non-thermoelectric renewable resource: hydroelectric power. Hydroelectric power plants "consume" a very large amount of water due to the increased evaporation rates associated with damming a waterway and creating a reservoir. Specifically, a hydroelectric power plant will "consume" (via direct evaporation) on average nearly 2,400% more water than a NGCC power plant to produce an equivalent amount of electricity. However, hydroelectric power reservoirs are typically used for many different purposes (i.e. drinking water supply and recreation) so power generation is not the sole cause of the evaporative losses. (USDOE 2006)

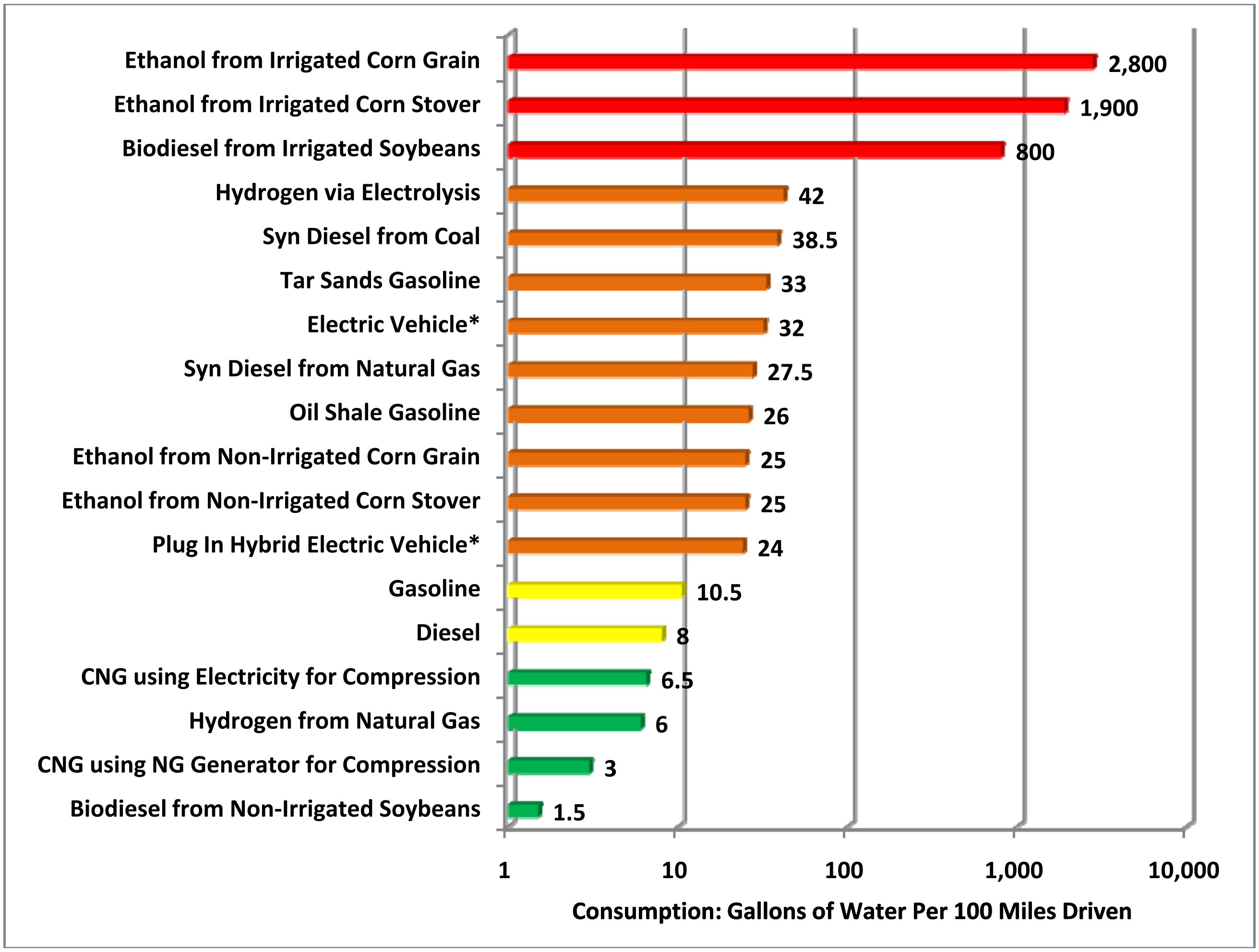
Overall, water withdrawal and water consumption are directly proportional to 1) efficiency of a power plant, and 2) fuel combustion temperature. For example, nuclear and coal plants have approximately the same generation efficiencies (33%), but nuclear power plants utilize much more water because all of the waste-heat must be transferred to the cooling water because there is no hot flue gas exhausted. However, this water consumption difference is slightly buffered due to the contrast in combustion temperatures between the two fuel types. Coal combustion occurs at a much higher temperature (1,500 ^{o}C) compared to nuclear (300 ^{o}C). This narrows the difference between the fuel sources, but coal / biomass power plants still remain more water efficient (compared to nuclear power plants) due to the partial discharge of waste-heat with the flue gas exhausted.

Transportation Fuel Water Use Efficiency

"Transportation is yet another area where the nexus between water and energy can potentially create conflicts where they did not exist before" (King and Webber 2008a). In the United States in 2005, 97% of all transportation was fueled by conventional petroleum based gasoline and diesel (with some fuels containing up to a 10% ethanol mixture to reduce air emissions) (King and Webber 2008a). Recently, there has been a significant push towards the use of non-conventional fossil fuels (liquid fuels derived from coal, oil shale, tar sands), biofuels (ethanol, biodiesel), compressed natural gas, hydrogen, and electricity for powering vehicles. A detailed look reveals some significant concerns and a few surprises related to water consumption and water withdrawal when considering these "alternative" transportation fuel sources.

Conventional petroleum-based fuels have historically had a relatively low impact on the water resources of the United States. According to King and Webber (2008a), conventional petroleum gasoline consumes between 7 and 14 gallons of water per one-hundred miles driven, and conventional petroleum diesel consumes between 5 and 11 gallons of water per one-hundred miles. "In general, fuels more directly derived from fossil fuels are less water intensive than those derived either indirectly from fossil fuels, or directly from biomass" (King and Webber 2008a). Detailed information is illustrated in Figure 6 below.

Figure 6: Water Intensity of Transportation Fuels



*Source: Adapted from King and Webber 2008a; *Adapted from King and Webber 2008b*

Figure 6 above is a logarithmic plot that shows 18 different transportation fuels and their respective water consumption reported in gallons of water per 100 miles driven. The different colors of the plots show:

- Green: Fuels that consume less water per mile than the traditional fuels
- Yellow: Traditional Fuels
- Orange: Higher water consumption than traditional fuels (200% - 525%)
- Red: *Significantly* higher water consumption than traditional fuels (1-3 orders of magnitude)

Figure 6 shows that the highest water consumption is associated with irrigated biofuels such as ethanol and biodiesel. This is expected due to the high irrigation and processing demands of the fuels as discussed in the raw water fuel efficiency section of this paper. Non-irrigated biofuels are much more efficient than their irrigated counterparts as illustrated above. Non-irrigated ethanol has a slightly higher water consumption than conventional fuels, but biodiesel derived from non-irrigated soybeans has the lowest water consumption of all fuels evaluated. However, the definition of water "intensity" as it relates to non-irrigation is subject to debate. While non-irrigated crops can be sustained with regular rainfall patterns, they still must use water, thus preventing that volume of water from being used for another purpose (runoff, aquifer recharge, or other uses). Furthermore, irrigation requirements are highly dependent on geography and non-irrigation is not an option in many core crop producing areas of the United States.

Unconventional fossil fuels such as tar sands gasoline, oil shale gasoline, and synthetic diesel from coal also have higher water consumption than their conventional counterparts due to the water intensive extraction and processing requirements to generate a useable liquid transportation fuel. Hydrogen, which must be generated from other sources, can be a relatively inefficient water consumer when generated via electrolysis, or in contrast, very efficient when generated from natural gas.

Recently, electric vehicles and plug-in hybrid vehicles have received substantial attention from the government, the media, and auto-makers. Many auto-makers are focusing research and development on these vehicles due to their perceived "green" image. However, the water demands these vehicles will have on water supplies has gone relatively unnoticed. According to King and Webber (2008b), and shown in the plot above, (in reference to conventional fuels compared to electric vehicles) "approximately three times more water is consumed and over 17 times more water is withdrawn primarily due to increased water cooling of thermoelectric power plants to accommodate increased electricity generation."

As illustrated in Figure 6, natural gas based transportation fuels are among the most water efficient fuels of all those evaluated. In fact, compressed natural gas (CNG) using a natural gas powered generator for compression of the fuel source, consumes only one-third of the water that conventional fuels do. Even using thermoelectric power (electricity) for compression of the CNG fuel, the water consumption is still lower than that of the conventional fuels.

Summary and Conclusion

Water is essential to energy resource development; conversely, energy resources are needed for developing, processing, and distributing water resources. As a result, water and energy are interdependent. This "balance" or "nexus" between resources is a critical, yet often overlooked component in evaluating energy resources. Recent technological advancements in horizontal drilling and hydraulic fracturing have unlocked an abundance of deep shale natural gas in the United States. This paper addressed the water efficiency of deep shale natural gas compared to other energy resources.

The water efficiency of transportation fuels was intentionally discussed after the raw fuel and power generation water efficiency topics for two principal reasons. The first reason is it ties both the raw fuel water efficiency and the power generation water efficiency topics together (compares biofuels and gasoline, to electrical vehicles). The second reason is transportation fuels are a "wild card" when discussing water efficiency. Tremendous amounts of water and energy are utilized in the United States in order to transport people and products (including, ironically, water and energy). Every time fuel is imported, it is important to consider the environmental impacts (including water consumption requirements) of transporting the fuel, as well as the net energy loss associated with transporting fuel (fuel is needed for transport). This is why from a water and energy perspective, domestically and even regionally produced fuels should be considered "greener" or of "higher environmental value".

Deep shale natural gas uses water primarily during drilling and stimulation, but produces a tremendous amount of energy over the approximate 20-year lifespan of the natural gas well. When compared against other energy resources (as discussed in this paper), it is by far the most water efficient of all the "baseload-level" energy resources, and when used for power generation in a NGCC power plant, is among the most water efficient at generating electricity. Furthermore, little used and often overlooked, compressed natural gas (CNG) is among the most water efficient transportation fuels available today.

Based on this water efficiency evaluation of raw fuel sources, power generation facilities, and transportation fuels, one clear statement comes forward: "Natural gas, including deep shale natural gas, ranks among the most abundant, most flexible, most affordable, and surprisingly most water efficient energy resources available today".

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