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Water Intensity Assessment of Shale Gas Resources in the Wattenberg Field in Northeastern Colorado

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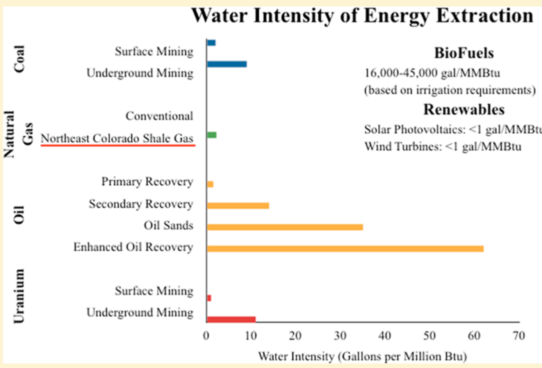
ABSTRACT: Efficient use of water, particularly in the western U.S., is an increasingly important aspect of many activities including agriculture, urban, and industry. As the population increases and agriculture and energy needs continue to rise, the pressure on water and other natural resources is expected to intensify. Recent advances in technology have stimulated growth in oil and gas development, as well as increasing the industry's need for water resources. This study provides an analysis of how efficiently water resources are used for unconventional shale development in Northeastern Colorado. The study is focused on the Wattenberg Field in the Denver–Julesberg Basin. The 2000 square mile field located in a semiarid climate with competing agriculture, municipal, and industrial water demands was one of the first fields where widespread use of hydraulic fracturing was implemented. The consumptive water intensity is measured using a ratio of the net water consumption and the net energy recovery and is used to measure how efficiently water is used for energy extraction. The water and energy use as well as energy recovery data were collected from 200 Noble Energy Inc. wells to estimate the consumptive water intensity. The consumptive water intensity of unconventional shale in the Wattenberg is compared with the consumptive water intensity for extraction of other fuels for other energy sources including coal, natural gas, oil, nuclear, and renewables. 1.4 to 7.5 million gallons is required to drill and hydraulically fracture horizontal wells before energy is extracted in the Wattenberg Field. However, when the large short-term total freshwater–water use is normalized to the amount of energy produced over the lifespan of a well, the consumptive water intensity is estimated to be between 1.8 and 2.7 gal/MMBtu and is similar to surface coal mining.



INTRODUCTION

Water use is a major concern related to the development of shale gas in semiarid regions of the western United States. Historical agricultural needs, burgeoning development, population growth, and considerable growth in oil and gas activity in these regions are all competing and placing growing demands on regional water and energy resources.

The development of unconventional shale resources requires large volumes of water, but the efficiency of the water use in terms of energy recovery is not often considered. Water and energy resources are intricately connected and cannot be assessed independently when formulating rational energy or water policies. A small number of studies have assessed the water use required for shale gas development,[1−3] future regional water demands,[4−6] and estimated energy recovery.[7] In 2006, Congress issued a directive asking for a report on energy and water interdependencies, focusing on threats to national energy production that might result from limited water supplies.[8] Increasing concerns about water and energy resources in the United States has led to significantly more available literature, particularly from government agencies.[9−11]

Water intensity is a common measure of how efficiently water resources are used to extract energy resources. For this study, the consumptive water intensity is defined as the ratio of the net consumption of water used and the net energy recovered. Although impacts beyond consumptive water intensity must be considered (e.g., water quality, air emissions, energy quality, short-term total freshwater–water use, etc.), consumptive water intensity provides a simple measure to compare the efficiency of water use for different energy sources.

Several studies have compared the water intensity values for other energy extraction processes, and others have expanded the water intensity to end-uses including electricity generation and transportation. Gleick[12] provided one of the first broad reviews of water intensity, presenting direct, consumptive water intensity values for each life cycle phase (i.e., extraction, preparation, electricity generation, etc.) of several different fuel sources in 1994. Other studies have expanded the definition of water intensity beyond consumed water to include embedded[13] and withdrawn[14] water. These definitions become more important when considering the water intensity of electricity

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generation and specific cooling methods (e.g., once-through, closed-loop).

This study examines the consumptive water intensity of unconventional shale gas resources in the Wattenberg Field, a 2000 square mile field in the Denver–Julesberg Basin. Niobrara shale is the primary target formation in the field, but requires horizontal drilling and hydraulic fracturing. The field is studied because hydraulic fracturing and horizontal drilling has brought rapid oil and gas development to a semiarid region with large agriculture water demands and a growing population. Water use and water efficiency is a central concern associated with oil and gas development in Northeastern Colorado. Although broad estimates of water use and water intensity in the Wattenberg are available,[2] a detailed assessment of individual wells has not been published.

The objective of this study is to provide a detailed assessment of the consumptive water intensity and water consumption for unconventional shale gas development in the Wattenberg Field and compare the water intensity with other energy extraction processes.

MATERIALS AND METHODS

Sampled Wells. Two-hundred randomly sampled wells were used to assess the water intensity of unconventional shale gas resources in the Wattenberg Field. The sampled wells were limited to the following criteria: located in the Wattenberg Field (as defined by the Colorado Oil and Gas Conservation Commission on July 1, 2013), operated by Noble Energy, Inc. (Noble), complete water and energy records, drilled between January 1, 2010 and July 1, 2013, and have at least 100 days of production data.

The sampled wells are represented as red dots in Figure 1. The Wattenberg Field, as defined by the Colorado Oil and Gas Conservation Commission on July 1, 2013, is shown in tan. The sampled wells are slightly skewed toward the Northeast part of the field, where the majority of Noble's wells are located.

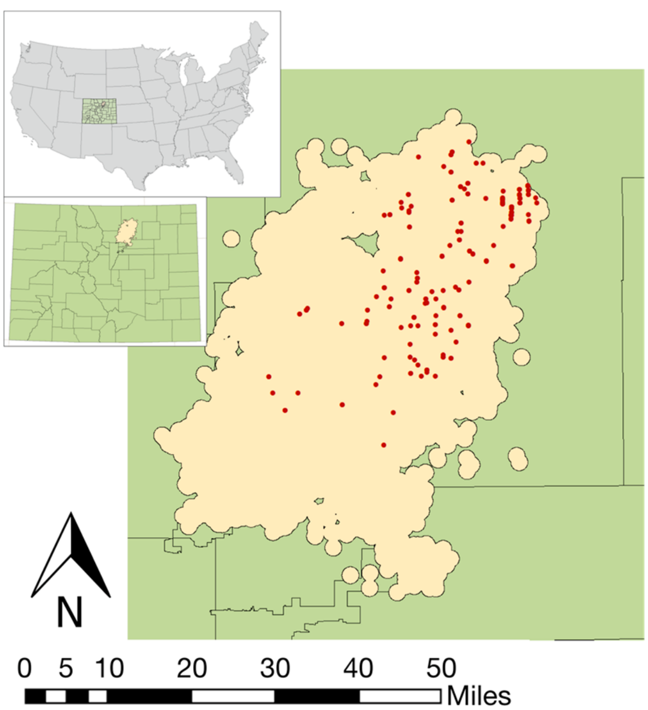

Figure 1. The sampled wells used in the study are shown in red. The Wattenberg is shown in tan along with Colorado county lines. The Wattenberg Field is located Northeast of Denver, Colorado.

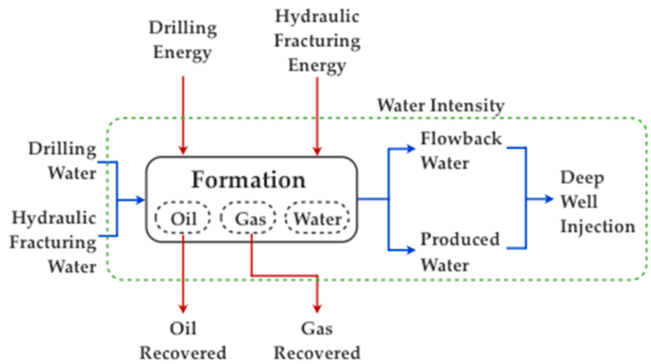

Figure 2. Water and energy balance defining the water intensity assessment. The blue lines represent the flow of water, the red lines represent the flows of energy, and the green line defines the system boundary for the water intensity assessment.

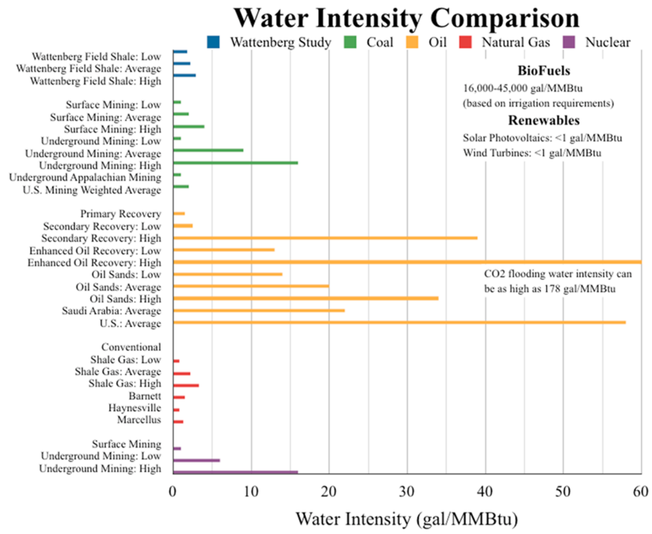

Figure 3. A comparison of the consumptive water intensity values for a variety of energy sources.

Data collected for each well includes: (a) drilling water use, (b) hydraulic fracturing water use, (c) total water use, (d) completion date, (e) location, (f) number of hydraulic fracturing stages, (g) oil recovered per day, and (h) gas recovered per day. All of the data were collected from Noble.

Water Use Data Collection. For this analysis, the volume of water used (or withdrawn) and volume of water consumed are the same because it is assumed that none of the flowback or produced water is treated for reuse for the development of new wells or any other beneficial reuse. The water used at each is recorded by the trucking companies and verified by Noble. Noble also records the intended use of the water (e.g., drilling, hydraulic fracturing, or potable water). Drilling water is defined as water that is used to drill the well, prepare the borehole, and set the casings. Hydraulic fracturing water is defined as water that is used to flush the borehole, fracture the shale, carry the proppant, and cleanout the borehole. Potable water volumes are negligible compared to drilling and hydraulic fracturing water volumes and not included in the assessment. The total water consumed for each well is defined as the sum of drilling and hydraulic fracturing water.

The volume of water consumed for drilling and hydraulic fracturing is collected using Merrick System's WellView software,[15] Noble's well data management software. All of the data were

Table 1. Consumptive Water Use Summary of the Sampled Wells

percentile	number of hydraulic fracturing stages	drilling water consumed	hydraulic fracturing water consumed	total water consumed	drilling water consumed	hydraulic fracturing water consumed	total water consumed
			(gallons)			(gallons per stage)	
10th	17	68 500	2 380 000	2 510 000	3300	126 000	133 000
25th	19	89 300	2 640 000	2 760 000	4370	138 000	144 000
50th	20	116 000	2 880 000	2 990 000	5690	146 000	152 000
75th	20	138 000	3 140 000	3 240 000	6880	156 000	162 000
90th	24	168 000	3 780 000	3 880 000	8760	181 000	186 000

Table 2. Energy Use Summary of the Sampled Wells

percentile	number of hydraulic fracturing stages	30-year oil EUR	30-year gas EUR	30-year total EUR	30-year oil EUR	30-year gas EUR	30-year total EUR
		(bbls)	(Mcf)	(MMBtu)	(bbls per stage)	(Mcf per stage)	(MMBtu per stage)
10th	17	72 800	301 000	878 000	3770	14 100	44 600
25th	19	90 200	373 000	1 080 000	4720	18 300	54 800
50th	20	122 000	551 000	1 310 000	6350	27 900	65 500
75th	20	165 000	819 000	1 790 000	8000	41 400	83 200
90th	24	246 000	1 170 000	2 220 000	9530	60 400	108 000

collected on July 1, 2013 from Noble's offices in Denver, Colorado.

Estimated Ultimate Energy Recovery Methods. The gross volume of crude oil and gas produced is measured prior to leaving the well site. Noble verifies the initial measurement by measuring the volume in oil storage tanks and by sending the gas through a check meter. The daily oil and gas production from each well is recorded and stored in a production database.

The daily oil and gas production records for each well through July 1, 2013 are collected from Noble's well production database, Merrick System's Carte software.[15] The data are fit to a harmonic decline curve (eq 1) with a least-squares fit using MATLAB's Curve-Fitting Toolbox to extrapolate future oil and gas production for each well. In eq 1, q_i is defines the initial rate of flow and D_i defines the effective decline rate. The estimated ultimate recovery of oil and gas assumes that the wells will be productive for a 30-year period. The sum of existing oil and gas production data and extrapolated production estimates is used to estimate the ultimate oil and gas recovered for each well. The energy density of oil and gas is assumed to be 5.6 MMBtu/BBL and 1.03 MMBtu/Mcf, respectively.

$$q(t) = \frac{q_i}{1 + D_i t} \tag{1}$$

Although diesel fuel is the primary energy source for drilling and hydraulic fracturing, several of the sampled wells used a combination of diesel and liquefied natural gas. The net diesel and liquefied natural gas volumes delivered to the each well is used to define the total energy consumed at each well. Diesel is assumed to have an energy density of 0.133 MMBtu/gal and liquefied natural gas is assumed to have an energy density of 0.080 MMBtu/gal.

Water Intensity Estimates. The water intensity is estimated by taking a ratio of the water consumed (sum of drilling and hydraulic fracturing water consumption) as the net energy produced (the difference between the estimated ultimate oil and gas recovery and the energy consumed for drilling and hydraulic fracturing). The water intensity is determined for each well.

RESULTS AND DISCUSSION

Water and Energy Use. The total water consumption for the sampled wells ranged from 1.4 to 7.5 million gallons of water, with a median of 3.0 million gallons of water per well. The wide-range of water use values for individual wells can be accounted for with the number of hydraulic fracturing stages. A horizontal well is hydraulically fractured in small sections, or stages, to optimize production. As the number of stages and horizontal length increases, the water use also increases.[16−19]

The number of hydraulic fracturing stages for the sampled wells ranged from 7 to 43, with 20 being the most common. A typical stage is approximately 250 feet. When the water consumption is normalized to the number of stages the median water use was 152 000 gallons per stage with an interquartile range of 18 000 gallons per stage.

Hydraulic fracturing used the majority (approximately 95%) of the total water consumed. The median water consumption for hydraulic fracturing was 2.88 million gallons (146 000 gallons per stage) with an interquartile range of 505 000 gallons (18 000 gallons per stage). The median water used for drilling was 2.88 million gallons (5690 gallons per stage) with an interquartile range of 48 900 gallons (2510 gallons per stage).

Drilling used the majority (approximately 98%) of the total energy consumed per well. The median drilling energy consumed was 3760 MMBtu per well and the median hydraulic fracturing energy consumption was 78 MMBtu per well. For an assessment of the net energy produced for each well, the total energy consumed became insignificant compared with the total energy recovered.

Energy Recovery. The estimated ultimate energy recovered (EUR) for 30-years of production without any restimulation was between 1.08 and 2.22 trillion Btu per well (54.8 to 83.3 billion Btu/stage), with a median of 1.31 trillion Btu per well (65 500 billion Btu/stage). Ultimate oil recovery was estimated to be between 90 200 and 165 000 bbls per well (4720 to 8000 bbls per stage). Ultimate gas recovery was estimated to be between 373 000 and 819 000 Mcf per well (18 300 to 41 400 Mcf/stage). With limited production data, there was a large uncertainty in the estimated ultimate recovery, as more production data in the region becomes available decline curve analyses can be refined.

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Water Intensity. Despite large uncertainties in the estimated ultimate energy recovered, water intensity had a relatively small range of 1.8 to 2.9 gal/MMBtu, with a median of 2.2 gal/MMBtu. The water intensity did not change with the number of hydraulic fracturing stages, because both the water consumption and energy recovery increase with more hydraulic fracturing stages Table 3. The water intensity for each well is estimated before the percentiles are estimated; for this reason, the ratio of the water use and energy recovery for a specific percentile may not be the same as the reported water intensity for the same percentile. Table 4 presents the extractive water intensity for a variety energy sources. The water intensity is defined in the same manner as this study, a ratio of the consumptive water use and the estimated ultimate energy recovered for each energy source.

Table 3. Water Intensity Summary of the Sampled Wells[a]

percentile	water intensity (gal/MMBtu)
10th	1.5
25th	1.8
50th	2.3
75th	2.9
90th	3.5

[a]The water intensity is defined as a ratio of the consumptive water use and the estimated ultimate energy recovered.

The water intensity of the sampled wells is similar to the water intensity of surface mining of coal (1−4 gal/MMBtu) and less than underground coal mining (1−16 gal/MMBtu).[12,13] Coal mining, like most mining processes, requires water throughout the entire extraction process and during processing to remove fines and clays. The water required for unconventional shale development is entirely consumed before oil and gas production begins, placing large short-term total freshwater−water use requirements on local water resources, particularly as a large field develops.

In order to reduce the water intensity and minimize the short-term total freshwater−water use, water treatment and reuse strategies are being implemented and refined in the field by Noble.[22−27] However, there are several challenges with reusing flowback and produced water. As the well ages, the wastewater quality transitions from a water quality that resembles the hydraulic fracturing fluid and is characterized by high gelled solids content to a water quality that is similar to the formation water quality and characterized by high total dissolved solids. Furthermore, the water quality varies throughout the field and with different hydraulic fracturing fluids.

These variations create challenges for treating the water to a consistent water quality, which is essential for gelled hydraulic fracturing fluid development and performance. Inconsistencies in the water quality used to develop hydraulic fracturing, or the use of other base fluids such as liquefied natural gas, fluid may influence how the gel cross-links (develops a high viscocity to carry the proppant) and breaks (decreases the viscocity in a controlled manner to release the proppant downhole) as well as how the water fluid interacts with the formation. This can dramatically influence oil and gas production for a well. A better understanding of flowback/produced water quality, water treatment targets, and the influence water quality has on the development and performance of gelled hydraulic fracturing fluids is necessary to optimize water reuse in the Wattenberg.

Table 4. Comparison of the Consumptive Water Intensity Values for a Variety of Energy Sources[a]

energy source	water intensity (gal/MMBtu)	source
Wattenberg Field Shale		
low	1.8	sampled wells
average	2.3	sampled wells
high	2.9	sampled wells
coal		
surface mining: low	1	12, 13
surface mining: average	2	12, 13
surface mining: high	4	12, 13
underground mining: low	1	12, 13
underground mining: average	9	12, 13
underground mining: high	16	12, 13
underground appalachian mining	1	12, 13
united state weighted average	2	12, 13
oil		
primary recovery	1.5	12
secondary recovery: low	2.5	20
secondary recovery: high	40	20
enhanced oil recovery: low	13	20
enhanced oil recovery: high	178	20
oil sands: low	14	12, 20
oil sands: average	20	12, 20
oil sands: high	34	12, 20
Saudi Arabia: average	22	21
United States: average	58	21
natural gas		
conventional	1.5	2, 9
shale gas: low	0.8	25
shale gas: average	2.2	25
shale gas: high	3.3	25
Barnett	1.5	2
Haynesville	0.8	2
Marcellus	1.3	2
nuclear		
uranium surface mining	1	2, 9, 12, 13
uranium underground mining: low	6	2, 9, 12, 13
uranium underground mining: high	16	2, 9, 12, 13
biofuels		
biofuels: low	2500	9
biofuels: high	29 000	9
non-irrigated corn ethanol: Indiana	83	21
irrigated corn ethanol: Kansas	3805	2

[a]The water intensity is defined as a ratio of the consumptive water use and the estimated ultimate energy recovered.

However, without water reuse strategies the consumptive water intensity over the lifespan of the sampled wells (1.8 to 2.9 gal/MMBtu) is similar to other energy extraction processes. Primary oil recovery (wellbore drilled into a reservoir) and conventional natural gas extraction both have a consumptive water intensity of approximately 1.5 gal/MMBtu.[2,9,12] Secondary recovery methods can increase the consumptive water intensity to 2.5 gal/MMBtu (steam stimulation) to 40 gal/MMBtu (polymer assisted water flooding).[20] Enhanced oil recovery methods, such as CO_2 flooding can increase the consumptive water intensity even further to between 13 gal/MMBtu and 178 gal/MMBtu.[20] Oil sands are also more water intense, with consumptive water intensities between 14 and 34 gal/MMBtu.[12,20]

The water intensity of uranium mining (1 gal/MMBtu for surface mining and 1 to 16 gal/MMBtu for underground

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mining)[13] is similar to coal mining. Renewable energy sources, particularly solar and wind are difficult to compare because extraction and electricity generation are not clearly separated. While small-scale solar photovolatiacs have been estimated to have a consumptive water intensity of less than 1 gal/MMBtu, large-scale concentrated solar photovoltaics (2500 gal/MMBtu), heliostats (1700 gal/MMBtu), and solar troughs (2900 gal/MMBtu) consume large volumes of water for cooling.[9,13] The consumptive water intensity of wind turbines is less than 1 gal/MMBtu, but the embedded water required to manufacture the turbines can range from 400 to 850 gal/MMBtu.[13,21]

Biofuels have some of the highest consumptive water intensities. The water intensity of biofuels is highly dependent on the irrigation requirements for a region. For example, one study estimates nonirrigated corn ethanol grown in Indiana has a water intensity of 83 gal/MMBtu and irrigated corn ethanol grown in Kansas has a water intensity of 3805 gal/MMBtu.[2,9,21]

As water resources in the western U.S. become increasingly strained due to competing demands from activities including, agriculture, urban, industry, and energy, it is important to consider the implications different fuel sources have on water resources. Although the extraction of natural gas consumes large volumes of water before energy is produced, the water intensity of extraction is similar to the consumptive water intensity of surface mining.

This study provides an assessment of how efficiently water is consumed to extract unconventional shale resources in the Wattenberg Field in northern Colorado. Energy related water issues are complicated, and an assessment of the consumptive only captures one impact of energy development. Although the consumptive water intensity for extraction of unconventional shale resources in the Wattenberg is relatively low, it is important to manage water responsibly to prevent short-term and local strains on water resources. Flowback and produced water must also be properly managed to minimize the environmental and public health risks.

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Notes

The authors declare no competing financial interest.

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■ REFERENCES

(1) Nicot, J.-P.; Scalon, B. R. Water use for shale-gas production in Texas, us. *Environ. Sci. Technol.* **2012**, *46* (6), 3580−3586.

(2) Mielke, E.; Anadon, L. D.; Narayanamurti, V. Water consumption of energy resource extraction, processing, and conversion, Discussion Paper 2010-15, Harvard Kennedy School Belfer Center for Science and International Affairs: 79 JFK Street, Cambridge, MA 02138 (October 2010).

(3) Clark, C. E.; Horner, R. M.; Harto, C. B. Life cycle water consumption for shale gas and conventional natural gas. *Environ. Sci. Technol.* **2013**, *47* (20), 11829−11836.

(4) Colorado Water Conservation Board, State of Colorado 2050 municipal and industrial water use projections, Tech. rep., Colorado Water Conservation Board, Camp Dresser and McKee Inc./Harvey Economics: (July 2010).

(5) Colorado's water supply future: State water supply initiative 2010, Tech. rep., Colorado Water Conservation Board: (January 2011).

(6) Nelson, P. H.; Santus, S. L. Gas, oil, and water production from wattenberg field in the Denver basin, Colorado. Open-File Report 2011−1175, United States Geological Survey: 2011.

(7) Kenny, J. F.; Barber, N. L.; Hutson, S. S.; , and Linsey, K. S. Estimated use of water in the united state in 2005. Circular 1344, United States Geological Survey: 2009.

(8) SAEB. Shale gas production subcommittee second ninety day report, Tech. rep., U.S. Department of Energy: (November 2011).

(9) U.S. Department of Energy. Energy demands on water resources, Tech. rep., U.S. Department of Energy: (2006).

(10) U.S. Department of Energy. Estimating freshwater needs to meet future thermoelectric generation requirements, Tech. Rep. 400/2008/1339, Department of Energy and National Energy Technology Laboratory: (September 2008).

(11) U.S. Department of Energy. State oil and natural gas regulations designed to protect water resources, Tech. rep., U.S. Department of Energy, Office of Fossil Energy, National Energy Technology Laboratory: (May 2009).

(12) Gleick, P. H. Water and energy. *Ann. Rev. Energy Environ.* **1994**, *19* (1), 267−299.

(13) Fthenakis, V.; Kim, H. C. Life-cycle uses of water in U.S. electricity generation. *Renew. Sust. Energy Rev.* **2010**, *14* (7), 2039−2048.

(14) Sovacool, B. K.; Sovacool, K. E. Preventing national electricity-water crisis areas in the united states, Tech. rep., Energy Governance Program at the Centre on Asia and Globalization, Lee Kuan Yew School of Public Policy at the National University of Singapore: (2009).

(15) Carte, Web-based oil and gas production reporting, Merrick Systems, Houston, TX, 2013.

(16) Well Surface Location Shapefile. Colorado Oil and Gas Conservation, Denver, CO, July 2013.

(17) *MATLAB*, version 7.10.1 (R2010a); The MathWorks Inc.: Natick, MA, 2010.

(18) Goodwin, S.; Carlson, K.; Bai, B.; Rein, L.; Knox, K.; Douglas, C. Improved Water Use Estimates for Drilling and Hydrualic Fracturing in Northeastern Colorado. *J. Water Resour. Protect.* **2013**, *5* (12), 1262−1267, DOI: 10.4236/jwarp.2013.512135.

(19) National Renewable Energy Laboratory. Emerging issues for fossil energy and water, Tech. rep., National Energy Technology Laboratory: (2006).

(20) Royce, B.; Kaplan, E.; Garrell, M.; Geffen, T. Enhanced oil recovery water requirements. *Environ. Geochem. Health* **1984**, *6* (2), 44−53.

(21) Wu, M.; Mintz, M.; Wang, M.; Arora, S. Water consumption in the production of ethanol and petroleum gasoline. *Environ. Manage.* **2009**, *44* (5), 981−997.

(22) Energy Information Administration. Annual electric generator report, Form EIA-860, Energy Information Administration: (April 2011).

(23) Kenny, J. F.; Barber, N. L.; Hutson, S. S.; Linsey, K. S. Estimated use of water in the united state in 2005, Circular 1344, United States Geological Survey: (2009).

(24) Tellinghuisen, S. Water conservation = energy conservation, A report for the CWCB, Western Resource Advocates: (June 2009).

(25) Mantell, M. E. Deep shale natural gas and water use, part two: Abundant, affordable, and still water efficient, Tech. rep., Chesapeake Energy Corporation: (2010).

(26) Prior, A.. Approaches for minimizing impacts to water. *Natural Gas Symposium*. Colorado State University: 2013.

(27) Grubert, E. A.; Beach, F. C.; Webber, M. E. Can switching fuels save water? A life cycle quantification of freshwater consumption for Texas coal- and natural gas-fired electricity. *Environ. Res. Lett.* **2012**, *7* (4), 045801.