Electronic Supplementary Material (ESI) for Energy & Environmental Science.

Supplemental Information for "Wells-to-Wheels: Water Consumption for Transportation Fuels in the United States"

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Introduction

The goal of this study was to quantitatively analyze the impact of transportation fuels on water resources in the United States. The transportation fuels analyzed in this study include petroleum gasoline and diesel, corn-based ethanol, soy-based biodiesel, compressed natural gas (CNG), electricity generated from different sources in the US grid, and compressed hydrogen gas (H_2). The results were extended to assess blended fuels including gasoline mixed with 10% corn-based ethanol by volume (E10) and gasoline mixed with 85% corn ethanol by volume (E85) and 20% soybean-based biodiesel (B20) for use in internal combustion engine vehicles (ICEV). Collectively these fuels account for the majority of current and predicted near-future energy consumption in passenger vehicles in the United States. The following sections contain figures, tables and other details in support of the main body of the text.

Conversion Factors

Quantities associated with literature including water consumption factors, energy contents, and market values were harmonized using the conversion factors shown in Table S.1. The units for the data presented in this supplemental information are associated with the system from which the data were derived (frequently gallons, pounds, and miles), but in the main text the compiled data were converted into SI units (liters, GJ, mm, hectares, kilograms, and kilometers) for appeal to a more general audience.

Table S.1. Conversion Factors Used in this Analysis[1]

Description	Conversion Factor
Crude oil energy content (lower heating value)	129,670 Btu/gal
Crude oil density	3.205 kg/gal
Bitumen energy content (lower heating value)	152,371 Btu/gal
Bitumen density	3.84 kg/gal
Coal density	6.79 kg/gal
Corn density	25.4 kg/bushel
Ethanol energy content (lower heating value)	76,330 Btu/gal
Ethanol density	2.98 kg/gal
Ethanol market value	$1.09/gal
Dissolved distillers grain market value	$0.0538/lb
Soybean density	27.2 kg/bushel
Soybean biodiesel energy content (lower heating value)	119,550 Btu/gal
Soybean biodiesel density	3.361 kg/gal
Soybean biodiesel market value	$0.547/lb
Soy meal energy content (lower heating value)	5,740 Btu/lb

[1] from GREET 2014

Description	Conversion Factor
Soy meal market value	\$0.01/lb
Glycerin energy content (lower heating value)	2,665 Btu/lb
Glycerin market value	\$0.25/lb
Natural gas energy content (lower heating value)	983 Btu/ft^3
U^{235} nuclear energy content	6,930,000 kWh/kg U^{235}
U^{235} fraction in nuclear fuel	3.5%
U^{235} fraction before enrichment	0.5%
H_2 energy content (lower heating value)	114,000 Btu/kg H_2

Petroleum Production Water Consumption Factors

Crude oil is used to produce petroleum-based fuels including gasoline and diesel. Crude oil used in refineries in the United States is derived from many sources including conventional recovery operations both onshore and off shore and increasingly from unconventional sources such as Canadian Oil sands and shale formations. Figure S.1 shows the water injection and petroleum production throughout the life cycle of a typical well. After the well is constructed, it produces petroleum during the primary production period until the reservoir pressure and production rate decline. External water is then used to restore pressure to the reservoir and begin a secondary recovery period when water is co-produced with the petroleum that can be recycled. The produced water to oil ratio rises over time until it is no longer economical to continue. At that point some wells using enhanced recovery technologies to increase the petroleum during a tertiary recovery period.

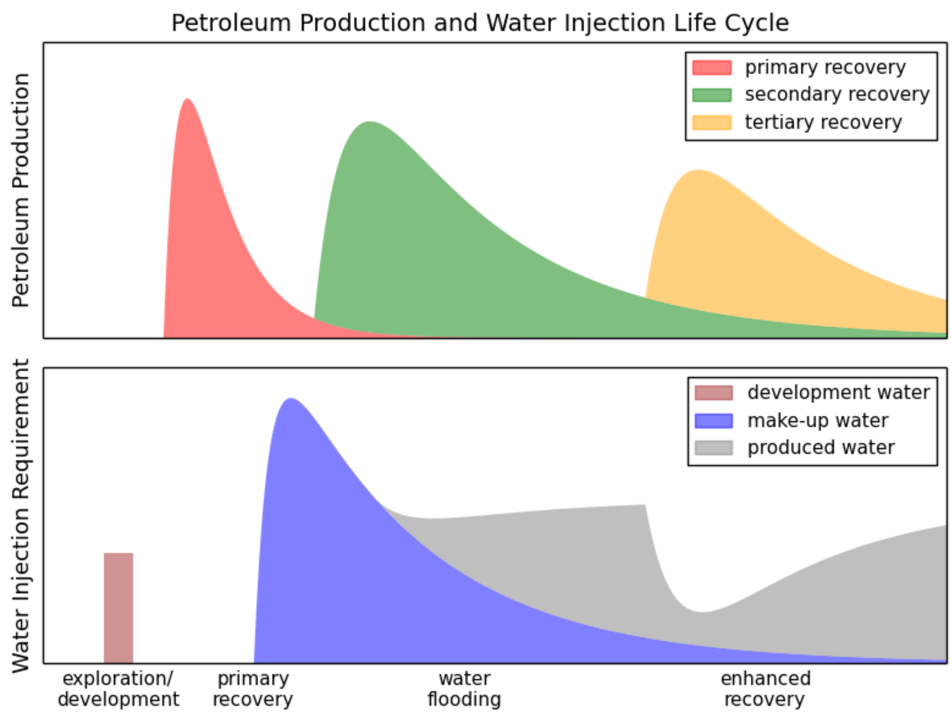

Figure S.1. Make-up water, produced water, and produced petroleum throughout a well life cycle.

Comprehensive estimates of the water volumes shown throughout the well life cycle illustrated in Figure S.1 are scarce. The majority of the literature estimates represent injection volumes relative to production for a given technology and a relatively short period of time. Quantifying the amount of injection water that originated outside the formation relative to production over a well life cycle can be challenging and is a topic in need of further research. The following paragraphs describe estimates water usage associated with various technologies used in crude oil production.

During primary production, reservoirs are pressurized and require little to no supplemental water for void replacement and stimulation. Large quantities of water are used to develop the well, but are relatively small when amortized over the life cycle production of the well. At a minimum, some water is always needed for drilling during the development period. Davis and Velikanov (1979) estimated that 45 million m^3 of water were used for drilling to produce 500 billion kg of petroleum in the United States. That estimate implies approximately 0.70 gal water per mmBtu of crude oil produced.

Following primary recovery, supplemental energy must be provided by drilling new wells and injecting water and/or other chemicals to stimulate the reservoir and re-establish production. Much of this water can be supplied by recycling the produced water. Supplemental water resources are often required during the initial stages of pressure re-establishment as shown in Figure S.1, however. The secondary recovery period is characterized by low initial production rates as the petroleum in the formation is displaced and pressure is re-established. Production levels rise as pressure is established and then decline as the water to oil ratio increases until it is no longer economical to continue. Bush and Helander (1968) analyzed secondary crude oil recovery for 86 sites where over 1.2 billion barrels of water were injected to produce 92.5 million barrels of crude oil (13 gal water per gal crude). Those data included water produced by the wells that was re-injected into the formation.

Following secondary recovery, the reservoir may be stimulated again using enhanced oil recovery (EOR) methods including injection of steam, gas, or chemicals in dilute aqueous solutions. Commonly used chemicals include surfactants, micellar polymers, and caustics. Gleick (1994) provided an overview of the amount of water injected per unit production in sites employing steam injection (3 to 5 gal water per gal crude) and caustic injection (3 gal water per gal crude). Miscible gases such as carbon dioxide are injected sometimes along with water to enhance recovery. In such operations, water is injected for void replacement and as a drive fluid, however. Royce et al. (1984) performed an industry survey for carbon dioxide enhanced recovery and reported an average of 13 gal of water per gal of crude. As in the case of secondary recovery, these estimates include re-injection of produced water.

Estimates of the amount of supplemental water needed for petroleum recovery are scarce and inconsistent. The Environmental Protection Agency (EPA) categorizes all wells used for subsurface injection into six classes. Class II wells are those associated specifically with petroleum and gas recovery operations. As of 2014, there were 172,068 Class II wells in the US (EPA, 2014). Each state has the option of regulating its own Class II wells following the demonstration that the state's regulation meets the EPA standard. There have been few efforts to compile comprehensive national-level inventories of water injections for petroleum recovery. Estimated injection volumes are further confounded by the re-injection of produced water.

Wu and Chiu (2011) combined water injection estimates from the literature described above with current technology shares to estimate a US average water injection volume of 8.0 gal of water injected per gal of crude produced. This value includes produced water re-injected into the formation. Veil et al. (2004) estimated state-level produced water and crude volumes, and the American Petroleum Institute (API) published state-level estimates of produced and re-injected water based on an industry survey (American Petroleum Institute, 2000). Wu and Chiu (2011) aggregated the data from these surveys to estimate the quantity of produced water re-injected for each Petroleum Administration for Defense District (PADD). They then used their estimated injection requirement of 8.0 gal water per gal crude to compute make-up water requirements of 2.1, 2.3, and 5.4 gal of make-up water required per gal of crude for PADDs II, III, and V. The estimated produced water re-injected in PADD I and PADD IV were greater than 8.0 gal per gal crude and were assumed to be negligible. Using the current PADD production share estimates (Energy Information Administration, 2014), a US production-weighted average WCF of 3.4 gal water per gal of crude for onshore production was computed.

Because of technological progress, US crude shares increasingly come from shale formations that require hydraulic fracturing and from Canadian oil sands. Recovery of bitumen from oil sands utilizes primarily two technologies—in-situ production and surface mining. Wu and Chiu (2011) indicated that surface mining operations consume an average of 4 gal water per gal bitumen based on an industry survey, while in-situ production consumes an average of 0.83 gal per gal bitumen using data and production shares from three mining operations. Scanlon et al. (2014) estimated water use for hydraulic fracturing in the Bakken and Eagle Ford tight oil plays, which accounted for approximately two-thirds of US unconventional production in 2013. Fracturing water use and recovery data for 8301 wells at Eagle Ford and 7868 in the Bakken were used to estimate the volume of water consumed per unit oil produced. The results indicated that 1.4 and 0.42 gal of water were used per gal oil in the Eagle Ford and Bakken formations, respectively.

Figure S.2 shows a comparison of the different injection and make-up water estimates for different technologies. While the range of these values is extensive (0 – 100 gal per mmBtu), it provides a basis for comparing water consumption between petroleum and other transportation fuel pathways.

Figure S.2. Make-up water, produced water, and produced petroleum (gal per mmBtu) throughout a well life cycle.

Biofuel Feedstock Production Water Consumption Factors

The methodology of Chiu and Wu (2012) was used to estimate state-level water consumption associated with corn and soybean farming. State-level crop production and irrigation withdrawal estimates were taken from the National Agricultural Statistics Service's (NASS) Census of Agriculture (NASS, 2014, 2009, 2004, 1999) and used to determine state-level water withdrawal factors (i.e., the volume of water withdrawn per unit crop produced). The withdrawal factors for corn grain and soybean production were estimated using acreage and irrigation application rates (volume water per acre farmed) from each census's corresponding Farm and Ranch Irrigation Survey (FRIS). Chiu and Wu (2012) used previous estimates (Solley et al., 1998) of state-level water withdrawals and consumption for irrigation from the United States Geological Survey (USGS) to extend water withdrawals to water consumption rates. The state-level ratios of irrigation water consumption to withdrawal from the USGS study were assumed to be representative of the withdrawal and return flows and were used to extend water withdrawal estimates to water consumption estimates. Soybean irrigation and production data were aggregated nationwide, while corn irrigation and production data were taken from the Midwestern states of Illinois, Indiana, Iowa, Minnesota, Nebraska, Ohio, Michigan, South Dakota, and Wisconsin. The state-level corn production and water consumption estimates appear in Table S.2 and Table S.3. The state-level soybean production and water consumption estimates appear in Table S.4 and Table S.5.

Table S.2. State-Level Corn Production

State	1997 Corn Production (bushels)	2002 Corn Production (bushels)	2007 Corn Production (bushels)	2012 Corn Production (bushels)
Alabama	20,608,991	15,241,418	21,008,771	25,998,347
Arizona	6,746,362	5,127,857	4,083,974	5,910,931
Arkansas	22,080,806	31,747,203	99,778,632	124,688,804
California	42,632,526	28,395,621	34,602,626	31,922,610
Colorado	131,492,974	102,653,083	140,523,805	121,002,552
Connecticut	612,648	361,647	424,350	806,003
Delaware	15,731,070	13,368,438	18,346,034	23,812,299
Florida	5,247,737	2,456,508	2,991,208	4,781,859
Georgia	41,144,090	26,720,244	54,137,330	52,451,141
Idaho	6,429,983	6,561,733	17,752,526	26,226,728
Illinois	1,372,414,201	1,418,566,127	2,248,664,947	1,253,283,049
Indiana	657,405,247	606,156,476	959,947,232	597,271,090
Iowa	1,581,093,092	1,851,276,224	2,292,163,101	1,835,358,239
Kansas	351,343,546	289,681,829	500,560,815	337,043,923
Kentucky	115,775,864	108,721,040	166,687,678	104,894,595
Louisiana	49,256,383	54,944,774	114,674,506	92,016,083
Maine	0	295,847	419,517	649,389
Maryland	36,641,509	30,041,896	45,548,271	50,114,967
Massachusetts	594,115	346,592	372,853	401,986
Michigan	245,261,942	234,709,542	288,066,336	313,802,471
Minnesota	796,829,406	989,887,877	1,138,660,229	1,297,767,570
Mississippi	44,879,039	58,487,848	127,841,765	127,937,980
Missouri	282,896,729	268,224,535	439,417,160	226,370,607
Montana	1,671,004	1,584,039	5,147,840	5,633,512
Nebraska	1,075,047,531	908,360,246	1,426,459,812	1,188,509,521
Nevada	37,232	34,447	73,176	489,627
New Hampshire	133,310	113,240	27,547	63,913
New Jersey	9,573,802	4,031,251	10,137,862	9,904,677
New Mexico	13,872,808	8,508,723	9,626,854	6,348,748
New York	65,729,918	42,767,720	71,454,280	87,677,512
North Carolina	74,291,257	58,918,039	98,245,673	93,402,417
North Dakota	56,335,638	111,380,248	275,329,681	406,059,209
Ohio	434,305,912	254,817,899	526,601,789	436,832,265
Oklahoma	20,964,252	23,642,448	38,603,555	30,391,761
Oregon	5,262,315	3,097,418	7,008,419	10,951,598
Pennsylvania	96,956,097	52,645,120	118,964,770	125,500,345
Rhode Island	0	3,616	3,207	35,570

State	1997 Corn Production (bushels)	2002 Corn Production (bushels)	2007 Corn Production (bushels)	2012 Corn Production (bushels)
South Carolina	29,125,176	11,147,604	35,122,617	35,597,075
South Dakota	302,695,636	295,166,830	518,552,101	480,330,680
Tennessee	59,605,812	64,081,209	83,636,352	81,645,799
Texas	224,990,592	197,109,321	286,386,341	204,454,091
Utah	2,642,441	2,134,158	3,249,594	5,379,627
Vermont	941,648	624,813	773,897	1,428,893
Virginia	29,903,600	22,656,691	34,811,582	33,984,647
Washington	16,725,028	14,155,973	24,553,928	23,824,561
West Virginia	3,291,931	3,057,437	2,916,834	4,554,125
Wisconsin	374,550,814	385,057,040	437,174,706	397,056,812
Wyoming	6,319,193	3,788,534	6,858,369	8,472,807
Totals	**8,732,091,207**	**8,612,858,423**	**12,738,394,452**	**10,333,043,015**

Table S.3. State-Level Corn Water Consumption

State	1997 Corn Water Consumption (acre-ft)	2002 Corn Water Consumption (acre-ft)	2007 Corn Water Consumption (acre-ft)	2012 Corn Water Consumption (acre-ft)
Alabama	5,509	5,135	16,878	14,220
Arizona	52,138	20,293	21,965	77,535
Arkansas	166,000	99,621	310,000	619,898
California	569,408	388,104	199,309	420,957
Colorado	471,884	365,342	492,417	360,896
Connecticut	0	0	0	0
Delaware	28,217	16,946	39,505	35,726
Florida	2,707	2,258	4,333	12,028
Georgia	116,286	39,094	170,539	151,931
Idaho	27,200	47,670	62,754	105,233
Illinois	102,437	133,475	154,594	263,069
Indiana	57,569	70,565	131,564	138,955
Iowa	21,807	35,631	53,990	70,759
Kansas	2,151,905	1,643,043	1,694,371	1,864,221
Kentucky	5,051	3,037	6,462	10,233
Louisiana	71,926	59,020	115,462	185,362
Maine	0	0	0	0
Maryland	12,886	5,208	27,199	20,033
Massachusetts	0	0	0	6
Michigan	107,029	88,393	142,040	142,713
Minnesota	61,852	94,846	136,412	142,965
Mississippi	59,512	49,416	202,021	365,835
Missouri	123,860	135,564	214,599	233,485
Montana	3,316	3,818	9,759	15,775
Nebraska	3,209,199	4,933,679	3,612,422	4,777,655

State	1997 Corn Water Consumption (acre-ft)	2002 Corn Water Consumption (acre-ft)	2007 Corn Water Consumption (acre-ft)	2012 Corn Water Consumption (acre-ft)
Nevada	0	0	0	0
New Hampshire	0	0	0	0
New Jersey	455	219	1,034	1,256
New Mexico	87,391	54,491	0	53,200
New York	141	154	130	823
North Carolina	7,115	4,641	37,107	11,416
North Dakota	24,419	46,737	64,810	57,554
Ohio	1,072	4,912	10,487	3,823
Oklahoma	76,827	63,476	61,846	69,747
Oregon	33,065	19,905	48,638	51,028
Pennsylvania	413	161	274	0
Rhode Island	0	0	0	0
South Carolina	7,771	5,599	28,329	20,721
South Dakota	64,177	92,476	91,387	91,044
Tennessee	3,227	2,943	10,676	27,928
Texas	1,482,094	1,032,913	1,397,017	1,091,658
Utah	31,518	18,909	41,101	48,736
Vermont	0	0	0	0
Virginia	3,468	2,027	3,819	3,644
Washington	66,580	57,087	91,316	89,182
West Virginia	0	0	0	0
Wisconsin	38,667	53,461	66,178	91,155
Wyoming	23,612	20,747	27,376	32,602
Totals	**9,379,706**	**9,721,020**	**9,800,117**	**11,775,006**

Table S.4. State-Level Soybean Production

State	1997 Soybean Production (bushels)	2002 Soybean Production (bushels)	2007 Soybean Production (bushels)	2012 Soybean Production (bushels)
Alabama	8,357,997	3,980,484	3,660,854	13,786,374
Arizona	0	0	0	0
Arkansas	104,706,642	96,257,992	98,903,025	136,482,368
California	0	0	0	0
Colorado	54,520	179,254	148,420	535,045
Connecticut	0	0	13,365	7,898
Delaware	6,638,933	4,717,471	3,990,694	7,066,569
Florida	988,263	242,878	291,981	723,143
Georgia	7,047,160	3,083,878	7,970,113	7,808,576
Idaho	0	0	0	0
Illinois	417,919,609	438,990,297	353,741,105	371,337,854
Indiana	212,463,202	235,450,361	211,074,079	218,928,307
Iowa	459,309,682	487,380,897	430,739,578	406,951,953

State	1997 Soybean Production (bushels)	2002 Soybean Production (bushels)	2007 Soybean Production (bushels)	2012 Soybean Production (bushels)
Kansas	76,267,366	57,946,285	82,719,224	83,696,476
Kentucky	43,487,052	43,939,662	29,582,097	56,450,394
Louisiana	37,571,260	20,736,686	24,717,263	51,467,676
Maine	21,743	34,009	22,570	87,088
Maryland	15,112,845	10,695,873	10,381,954	21,593,477
Massachusetts	8,510	2,632	10,530	32,722
Michigan	64,787,800	78,197,248	67,515,728	83,173,727
Minnesota	239,041,962	303,069,928	259,891,979	293,830,150
Mississippi	60,916,699	43,077,995	54,316,854	86,976,455
Missouri	170,632,278	165,048,253	165,947,323	148,826,538
Montana	0	0	16,084	163,125
Nebraska	133,244,032	173,029,716	189,547,373	193,014,515
Nevada	0	0	0	0
New Hampshire	6,293	0	0	900
New Jersey	3,581,578	2,301,468	2,443,231	3,746,674
New Mexico	4,253		0	0
New York	3,976,646	4,472,702	7,456,657	13,078,638
North Carolina	35,744,328	31,026,968	29,142,115	60,635,686
North Dakota	33,401,430	87,793,840	106,556,290	153,601,859
Ohio	174,584,429	149,809,069	191,559,567	202,032,493
Oklahoma	9,544,400	6,218,396	4,559,245	3,639,154
Oregon	0	0	0	999
Pennsylvania	13,487,668	9,665,498	17,386,829	25,008,038
Rhode Island	0	0	0	0
South Carolina	11,991,017	5,897,022	7,833,696	12,267,729
South Dakota	110,801,775	126,607,265	130,377,538	130,534,273
Tennessee	39,021,072	33,646,638	18,552,793	45,165,597
Texas	10,507,744	5,415,147	3,439,765	2,790,641
Utah	0	0	0	0
Vermont	37,867	51,289	75,318	222,023
Virginia	11,562,591	11,025,598	12,624,547	22,680,879
Washington	0	0	27,781	0
West Virginia	487,373	621,463	480,186	1,002,947
Wisconsin	42,996,339	67,060,605	54,701,222	67,454,065
Wyoming	0	0	0	0
Totals	**2,560,314,358**	**2,707,674,767**	**2,582,418,973**	**2,926,803,025**

Table S.5. State-Level Soybean Water Consumption

State	1997 Soybean Water Consumption (acre-ft)	2002 Soybean Water Consumption (acre-ft)	2007 Soybean Water Consumption (acre-ft)	2012 Soybean Water Consumption (acre-ft)
Alabama		179	5,267	6,154
Arizona	0	0	0	0
Arkansas	1,322,309	997,400	1,441,813	1,916,094
California	0	0	0	0
Colorado	2,162	1,191	2,242	4,216
Connecticut	0	0	0	4
Delaware	8,409	3,168	20,262	16,186
Florida	0	1,911	106	1,441
Georgia	11,342	6,411	42,973	22,014
Idaho	0	0	0	805
Illinois	49,721	61,138	45,249	78,527
Indiana	21,329	26,911	45,849	35,280
Iowa	8,308	21,503	19,578	25,211
Kansas	279,111	325,939	377,838	271,248
Kentucky	3,790	2,150	2,263	3,810
Louisiana	35,429	34,675	100,354	163,356
Maine	0	0	0	2
Maryland	9,918	2,712	14,408	12,087
Massachusetts	0	0	0	0
Michigan	41,775	27,546	35,200	31,936
Minnesota	18,521	55,030	53,778	50,677
Mississippi	237,703	152,854	363,502	524,676
Missouri	98,354	114,747	253,805	270,878
Montana	0	681	133	1,132
Nebraska	515,813	1,658,985	1,217,455	1,554,960
Nevada	0	0	0	0
New Hampshire	0	0	0	0
New Jersey	407	127	629	974
New Mexico	0	0	0	0
New York	0	0	0	0
North Carolina	966	0	37,098	3,596
North Dakota	1,883	10,750	11,898	12,095
Ohio	278	0	5,245	595
Oklahoma	6,962	6,295	8,834	18,987
Oregon	0	0	0	0
Pennsylvania	30	22	73	34
Rhode Island	0	0	0	0
South Carolina	4,611	2,295	7,645	4,140
South Dakota	21,103	52,389	25,793	30,331
Tennessee	2,113	3,032	16,395	17,258

State	1997 Soybean Water Consumption (acre-ft)	2002 Soybean Water Consumption (acre-ft)	2007 Soybean Water Consumption (acre-ft)	2012 Soybean Water Consumption (acre-ft)
Texas	86,494	50,274	26,364	27,695
Utah	246	0	0	0
Vermont	0	0	0	0
Virginia	1,745	479	2,639	2,478
Washington	0	0	314	622
West Virginia	42	0	0	0
Wisconsin	11,847	19,684	16,303	17,766
Wyoming	0	0	0	4,618
Totals	**2,803,120**	**3,640,478**	**4,201,304**	**5,131,881**

Petroleum Life Cycle Water Consumption Results

The main body of the manuscript describes the estimation of the life cycle water consumption associated with petroleum gasoline and diesel. The data used in the figure depicted in the main text are shown in Table S.6.

Table S.6. Water Consumption throughout Petroleum Life Cycle (gal per mmBtu)

Process	Gasoline	Diesel
Petroleum Recovery	25.538	25.538
Electricity Generation	9.411	8.380
Petroleum Refining	6.6	7.7
Transportation & Processing Fuels	4.692	1.365
Total	**46.241**	**42.983**

Corn Ethanol and Soy Biodiesel Life Cycle Water Consumption Results

The main body of the manuscript describes the estimation of the life cycle water consumption associated with corn ethanol and soy biodiesel. Table S.7 shows water consumption throughout the life cycle before allocation to co-products such as animal feed, glycerin, and other bioproducts.

Table S.7. Water Consumption throughout Biofuel Life Cycle (gal per mmBtu)

Process	Corn Ethanol	Soybean Biodiesel
agricultural chemicals	134.7	14.1
Irrigation (1997, 2002, 2007 & 2012 average)	976.7	2751.1
biofuel conversion	37.2	40.9
other processes	27.9	38.4
Total	**1176.5**	**2844.6**

Corn Ethanol Co-Product Allocation

Corn ethanol is co-produced with distillers grains with solubles (DGS) in wet (11.4%) and dry-mill (88.6%) refineries. The material and energy inputs and outputs to a dry-mill corn ethanol refinery based on the US averages in GREET on a one gal of ethanol basis are shown in Table S.8.

Table S.8. Material and Energy Inputs to US Dry Mill Ethanol Biorefineries[2]

Item	Quantity	Units
Inputs		
Corn	9066	g
Natural Gas	22377	Btu
Coal	1946	Btu
Electricity	2533	Btu
Alpha Amylase	2.57	g
Gluco Amylase	5.53	g
Yeast	2.80	g
Water	2.7	gal
Outputs		
Ethanol	1	gal
DGS	2556	g

The water consumption burden was divided between the ethanol and DGS using a number of allocation methodologies. The densities, lower heating values, and market values shown in Table S.1 can be used to compute the mass, energy, and market value of the biorefinery products and then compute the fraction of the total for each methodology as shown in Table S.9. In addition to methods based on mass, energy, and market value, the water consumption can also be allocated by subtracting the water consumption required to produce resources displaced by the co-product (Wang et al., 2011). The resources displaced by 1 gram of DGS are 0.781 g corn, 0.307 g soy meal, and 0.0226 g urea (Arora et al., 2008). The water consumption in the displaced resources was computed using GREET and then used to allocate the water consumption burden between ethanol and DGS as shown in Table S.9.

Table S.9. Allocation between Ethanol and DGS in Dry-Mill Corn Ethanol Biorefineries

Allocation Basis	Ethanol	DGS
Mass	0.538	0.462
Energy	0.609	0.391
Market Value	0.783	0.217
Displacement	0.612	0.388

[2] from GREET 2014 (Wang et al., 2011)

Soybean Biodiesel Co-Product Allocation

Soy biodiesel is produced from soy oil in biodiesel refineries following extraction of the oil from soybeans. The extraction and refining processes co-produce glycerin and soymeal. The water consumption from the biodiesel refineries was allocated between the biodiesel and these co-products. The inputs and outputs of the soy oil extraction process on a one pound of soy oil produced are show in Table S.10, while the inputs and outputs to the transesterification process on a per pound of biodiesel produced are shown in Table S.11.

Table S.10. Material and Energy Inputs to the Soy Oil Extraction Process[3]

Item	Quantity	Units
Inputs		
Soybeans	2132	g
Natural Gas	2068	Btu
Coal	1018	Btu
Electricity	446	Btu
n-Hexane	59.0	Btu
Residual Oil	32.1	Btu
Outputs		
Soy Oil	454	g
Soy Meal	1677	g

Table S.11. Material and Energy Inputs to the Soy Oil Transesterification Process[3]

Item	Quantity	Units
Inputs		
Soy Oil	472	g
Sodium Hydroxide	0.441	g
Phosphoric Acid	0.29	g
Hydrochloric Acid	19.7	g
Methanol	785	Btu
Natural Gas	372	Btu
Electricity	55.8	Btu
Water	0.66	gal
Outputs		
Biodiesel	454	g
Glycerin	54.4	g

As in the case of corn ethanol, a number of methodologies were used to allocate the water consumption burden between co-produced biodiesel, glycerin, and soy meal derived from soybeans including mass,

[3] from GREET 2014 (Wang et al., 2011)

energy, and market value basis. The chemical properties and estimated market values from GREET 2014 summarized in Table S.1 were used to compute the relative mass, energy, and market values of the products on a per pound of biodiesel basis as summarized in Table S.12. The water consumption can be allocated to the glycerin and soy meal co-products on the basis of mass, energy, or market value, and therefore there are nine combinations of allocation methodologies. A mass-based allocation to both glycerin and soy meal provides the least burden to the biodiesel, while a market-based allocation to soy meal and an energy-based allocation to glycerin burdens biodiesel production the most.

Table S.12. Relative Outputs of Biodiesel, Soy Meal, and Glycerin from Soybean Biodiesel Production

Output	**Biodiesel**	**Glycerin**	**Soy Meal**
Mass (g)	454	54.4	1743
Energy (Btu)	16,149	319	22,017
Market Value	$0.546	$0.030	$0.038

Compressed Natural Gas Life Cycle Water Consumption

The main body of the text describes the production pathways for compressed natural gas (CNG). The CNG production pathways consist of recovery of raw natural gas followed by processing, transportation, and compression. The transportation and compression processes utilize no water directly but consume electricity which has a high embedded water consumption associated with power generation upstream. The water consumption associated with the processes in the CNG pathways is shown in Table S.13.

Table S.13. Water Consumption (gal per mmBtu) Associated with CNG Production

	Conventional	**Barnett**	**Marcellus**	**Fayetteville**	**Haynesville**	**US Average**
Processing	1.7	1.7	1.7	1.7	1.7	1.7
Compression	11.69	11.69	11.69	11.69	11.69	11.69
Processing & Transportation Fuel	1.93	1.93	1.93	1.93	1.93	1.93
Recovery	0.11	3.85	2.65	5.1	2.65	1.10
Total	**15.42**	**19.16**	**17.96**	**20.41**	**17.96**	**16.41**

Life Cycle Water Consumption Associated with Electricity Generation

The main body of the text describes the life cycle water consumption associated with electricity generation technologies including coal, natural gas, petroleum, nuclear power, hydropower, wind, geothermal power, biomass, and solar power plants. Renewable technologies require no fuel production and therefore the life cycle water consumption is the same as the process-level water consumption. The water consumption associated with various stages in the life cycle appears in Table S.14 and Table S.15.

Table S.14. Water Consumption Associated with Electric Power Plants (gal per kWh)

Process	Coal	Petroleum	Natural Gas	Nuclear	Biomass
coal power plant	0.541	0.009	0.002	0.004	0.001
coal fuel cycle	0.032	0.001	0.000	0.000	0.000
petroleum power plant	0.000	0.239	0.000	0.000	0.000
petroleum fuel cycle	0.005	0.369	0.001	0.000	0.018
natural gas power plant	0.000	0.002	0.219	0.001	0.000
natural gas fuel cycle	0.000	0.002	0.021	0.000	0.000
nuclear power plant	0.001	0.005	0.001	0.582	0.000
nuclear fuel cycle	0.000	0.000	0.000	0.082	0.000
biomass	0.000	0.000	0.000	0.000	0.610
municipal waste	0.000	0.000	0.000	0.000	0.000
geothermal power plant	0.000	0.000	0.000	0.000	0.000
wind power plant	0.000	0.000	0.000	0.000	0.000
solar power plant	0.000	0.000	0.000	0.000	0.000
hydropower plant	0.007	0.052	0.008	0.023	0.003
Total	**0.586**	**0.680**	**0.252**	**0.693**	**0.632**

Table S.15. Water Consumption Associated with Renewable Electricity Technologies

Technology	Water Consumption (gal per kWh)
municipal waste	0.610
geothermal power plant	1.199
wind power plant	0.001
solar power plant	0.045
hydropower plant	18.27

Electricity generation in the United States is governed by a number of different organizations that generate power using the technologies listed in Table S.14 and Table S.15. The water consumption for individual technologies was extended to analyze water in regional mixes as described in the main body of the text. The results are shown in Table S.16.

Table S.16. Water Consumption Associated with Electric Power Generation Mixes (gal per kWh)

Generation Mix	US	CA	FRCC	MRO	NPCC
coal power plant	0.241	0.036	0.133	0.348	0.025
coal power plants	0.013	0.002	0.007	0.019	0.001
coal fuel production	0.001	0.000	0.000	0.001	0.002
petroleum power plants	0.004	0.001	0.002	0.004	0.003
petroleum fuel production	0.062	0.121	0.134	0.004	0.102
natural gas power plants	0.005	0.010	0.011	0.000	0.008
natural gas fuel	0.122	0.052	0.071	0.070	0.173

Generation Mix	US	CA	FRCC	MRO	NPCC
production					
nuclear power plants	0.017	0.007	0.010	0.010	0.025
nuclear fuel production	0.001	0.001	0.001	0.003	0.006
biomass power plants	0.001	0.002	0.002	0.000	0.000
municipal waste power plants	0.006	0.059	0.000	0.000	0.000
geothermal power plants	0.000	0.000	0.000	0.000	0.000
wind power plants	0.000	0.002	0.000	0.000	0.000
solar power plants	1.350	2.630	0.135	0.950	2.588
hydropower plants	0.241	0.036	0.133	0.348	0.025
Total	**1.82**	**2.92**	**0.51**	**1.41**	**2.93**

Generation Mix	RFC	SERC	SPP	TRE	WECC
coal power plant	0.296	0.251	0.235	0.203	0.148
coal power plants	0.016	0.013	0.013	0.011	0.008
coal fuel production	0.001	0.001	0.000	0.000	0.000
petroleum power plants	0.004	0.004	0.004	0.003	0.002
petroleum fuel production	0.031	0.050	0.047	0.089	0.067
natural gas power plants	0.003	0.004	0.004	0.007	0.005
natural gas fuel production	0.160	0.155	0.018	0.070	0.046
nuclear power plants	0.023	0.022	0.003	0.010	0.007
nuclear fuel production	0.001	0.002	0.018	0.001	0.002
biomass power plants	0.000	0.000	0.000	0.000	0.000
municipal waste power plants	0.000	0.000	0.001	0.000	0.028
geothermal power plants	0.000	0.000	0.000	0.000	0.000
wind power plants	0.000	0.000	0.004	0.000	0.001
solar power plants	0.221	0.610	3.473	0.052	4.289
hydropower plants	0.296	0.251	0.235	0.203	0.148
Total	**0.75**	**1.11**	**3.82**	**0.45**	**4.60**

Life Cycle Water Consumption Associated with Compressed Hydrogen Fuel Production

The main body of the text describes the production life cycle of compressed hydrogen gas in detail. The pathways analyzed include steam methane reforming (SMR), electrolysis, and gasification of coal, coke, and a number of different kinds of biomass. The water consumption associated with feedstock production, process electricity, process natural gas, conversion, and compression are summarized in Table S.17.

Table S.17. Water Consumption (gal per kg H_2) Associated with Compressed Hydrogen Gas Production

Pathway	Feedstock Production	Process Electricity	Conversion Process	Electric Compression	Total
Central SMR	0.67	1.02	3.10	5.68	**10.47**
Distributed SMR	0.48	2.02	6.06	5.68	**14.25**
Coal Gasification	0.29	0.00	7.58	5.68	**13.55**
Switchgrass Gasification	1.20	1.79	4.34	5.68	**13.01**
Forest Residue Gasification	0.50	1.79	4.34	5.68	**12.32**
Willow Gasification	0.20	1.79	4.34	5.68	**12.01**
Central Electrolysis (Wind)	0.00	0.00	3.53	0.00	**3.53**
Distributed Electrolysis	0.00	82.36	5.80	5.68	**93.84**

Life Cycle Water Consumption per Unit Energy

The water consumption associated with the production life cycle for each of the fuels was compiled to a functional unit of gal per mmBtu. The results for petroleum, natural gas, and biofuels are shown in Table S.18, while the results for electricity generation and hydrogen fuel cell technologies are in Table S.19 and Table S.20.

Table S.18. Life Cycle Water Consumption (gal per mmBtu) Associated with Petroleum, Natural Gas, and Biofuels

Fuel	Gasoline (Petroleum)	Diesel (Petroleum)	Ethanol (Corn)	Biodiesel (Soybeans)	Compressed Natural Gas
petroleum fuel cycle	36.83	34.603	2.208	1.527	0.179
coal fuel cycle	0.063	0.055	0.279	0.127	0.104
natural gas fuel cycle	0.334	0.297	1.129	0.417	2.902
nuclear fuel cycle	0.086	0.075	0.182	0.115	0.127
electricity generation	8.787	7.685	19.839	11.864	13.126
hydrogen generation	0.141	0.268	0.039	0.082	0.003
agricultural chemical production	0	0	101.768	2.983	0
irrigation	0	0	376.857	620.733	0
Total	**46.241**	**42.983**	**539.514**	**676.63**	**16.441**

Table S.19. Life Cycle Water Consumption (gal per mmBtu) Associated with Electricity Generation Pathways

	Electricity (Coal)	Electricity (Natural Gas)	Electricity (Nuclear)	Electricity (Hydropower)	Electricity (Wind)
petroleum fuel cycle	1.590	0.319	0.119		
coal fuel cycle	9.986	0.028	0.077		
natural gas fuel cycle	0.024	6.557	0.046		
nuclear fuel cycle	0.030	0.034	25.868		
electricity generation	172.273	72.199	191.416	5354.408	0.293
hydrogen generation	0.029	0.005	0.002		
Total	**183.932**	**79.142**	**217.528**	**5354.408**	**0.293**

Table S.20. Life Cycle Water Consumption (gal per mmBtu) Associated with Hydrogen Fuel Pathways

	Compressed Hydrogen (Natural Gas)	Compressed Hydrogen (Coal)	Compressed Hydrogen (Biomass)
petroleum fuel cycle	0.355	0.888	2.261
coal fuel cycle	0.572	0.51	0.616
natural gas fuel cycle	3.978	0.204	0.458
nuclear fuel cycle	0.76	0.674	0.820
electricity generation	78.716	69.782	84.818
hydrogen generation	27.202	66.486	38.117
agricultural chemical production	0	0	3.647
Total	**111.583**	**138.544**	**130.7365**

Life Cycle Water Consumption per 100 Miles Traveled in Light-Duty Vehicles

The life cycle water consumption associated with transportation derived from each fuel was compiled to a functional unit of gal per 100 miles in a light-duty vehicle using the fuel economies shown in Table S.21 for internal combustion engine vehicles (ICEV), compressed natural gas vehicles (CNGV), battery electric vehicles (BEV) using electricity from the major sources in the US grid, and fuel cell electric vehicles (FCEV) powered by hydrogen gas produced from natural gas, electricity, coal, and biomass. The results are summarized in Table S.22 and Table S.23.

Table S.21. Fuel Economies of Light-Duty Vehicles (Argonne National Laboratory, 2014)

Vehicle	Fuel	Fuel Economy (btu per mile)
ICEV	E10	4961
ICEV	E85	4961
ICEV	Petroleum Diesel	4134
ICEV	Biodiesel	4134
ICEV	B20	4134
CNGV	CNG	5222
BEV	Electricity (US Mix)	1459
FCEV	Compressed H_2 (SMR)	2362
FCEV	Compressed H_2 (Electrolysis)	2362
FCEV	Compressed H_2 (Gasification)	2362

Table S.22. Life Cycle Water Consumption (gal per 100 miles) Associated with Liquid Fuels

Vehicle	ICEV (E10)	FFV (E85)	ICEV (Diesel)	ICEV (Biodiesel)	ICEV (B20)
petroleum fuel cycle	16.588	3.964	14.305	0.631	11.570
coal fuel cycle	0.042	0.121	0.023	0.053	0.029
natural gas fuel cycle	0.204	0.494	0.123	0.172	0.133
nuclear fuel cycle	0.047	0.082	0.031	0.048	0.034
electricity generation	4.897	8.926	3.177	4.905	3.522
hydrogen generation	0.065	0.028	0.111	0.034	0.095
agricultural chemicals	4.948	42.056	0.000	1.233	0.247
irrigation	18.322	155.737	0.000	256.611	51.322
biofuel conversion	1.809	15.378	0.000	16.032	3.206
Total	**46.922**	**226.786**	**17.769**	**279.719**	**70.159**

Table S.23. Life Cycle Water Consumption (gal per 100 miles) Associated with Alternative Fuels

Vehicle	CNGV	BEV (US Mix)	FCEV (SMR)	FCEV (Electrolysis)	FCEV (Gasification)
petroleum fuel cycle	0.093	0.192	0.084	0.403	0.210
coal fuel cycle	0.054	0.608	0.135	1.297	0.120
natural gas fuel cycle	1.515	0.253	0.940	0.507	0.048
nuclear fuel cycle	0.066	0.737	0.180	1.724	0.159
electricity generation	6.854	76.358	18.593	178.481	16.483
hydrogen generation	0.002	0.002	6.425	16.583	15.704
Total	**8.585**	**78.150**	**26.356**	**198.996**	**32.724**

References

American Petroleum Institute, 2000. Overview of Exploration and Production Waste Volumes and Waste Management Practices in the United States.

Argonne National Laboratory, 2014. Argonne GREET Model [WWW Document]. URL https://greet.es.anl.gov/ (accessed 5.7.15).

Arora, S., Wu, M., Wang, M., 2008. Update of distillers grains displacement ratios for corn ethanol life-cycle analysis. Cent. Transp. Res. Energy Syst. Div. Argonne Natl. Lab. January 2010.

Bush, J.L., Helander, D.P., 1968. Empirical prediction of recovery rate in waterflooding depleted sands. J. Pet. Technol. 20, 933–943.

Chiu, Y.-W., Wu, M., 2012. Assessing county-level water footprints of different cellulosic-biofuel feedstock pathways. Environ. Sci. Technol. 46, 9155–9162.

Davis, G.H., Velikanov, A.L., 1979. Hydrological problems arising from the development of energy: a preliminary report, in: Unesco Technical Papers in Hydrology. Unesco.

Energy Information Administration, 2014. Annual Energy Outlook 2014.

Gleick, P.H., 1994. Water and energy. Annu. Rev. Energy Environ. 19, 267–299.

NASS, 2014. 2012 Census of Agriculture.

NASS, 2009. 2007 Census of Agriculture.

NASS, 2004. 2002 Census of Agriculture.

NASS, 1999. 1997 Census of Agriculture.

Royce, B., Kaplan, E., Garrell, M., Geffen, T.M., 1984. Enhanced oil recovery water requirements. Miner. Environ. 6, 44–53.

Veil, J.A., Puder, M.G., Elcock, D., Redweik Jr, R.J., 2004. A white paper describing produced water from production of crude oil, natural gas, and coal bed methane. Prep. Argonne Natl. Lab. US Dep. Energy Natl. Energy Technol. Lab. January Available Httpwww Ead Anl Govpubdspdetail Cfm.

Wang, M., Huo, H., Arora, S., 2011. Methods of dealing with co-products of biofuels in life-cycle analysis and consequent results within the US context. Energy Policy 39, 5726–5736.

Wu, M., Chiu, Y., 2011. Consumptive Water Use in the Production of Ethanol and Petroleum Gasoline–2011 update. Energy Syst. Div.