Policy Analysis

Water Intensity of Transportation

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As the need for alternative transportation fuels increases, it is important to understand the many effects of introducing fuels based upon feedstocks other than petroleum. Water intensity in "gallons of water per mile traveled" is one method to measure these effects on the consumer level. In this paper we investigate the water intensity for light duty vehicle (LDV) travel using selected fuels based upon petroleum, natural gas, unconventional fossil fuels, hydrogen, electricity, and two biofuels (ethanol from corn and biodiesel from soy). Fuels more directly derived from fossil fuels are less water intensive than those derived either indirectly from fossil fuels (e.g., through electricity generation) or directly from biomass. The lowest water consumptive (<0.15 gal H_2O/mile) and withdrawal (<1 gal H_2O/mile) rates are for LDVs using conventional petroleum-based gasoline and diesel, nonirrigated biofuels, hydrogen derived from methane or electrolysis via nonthermal renewable electricity, and electricity derived from nonthermal renewable sources. LDVs running on electricity and hydrogen derived from the aggregate U.S. grid (heavily based upon fossil fuel and nuclear steam-electric power generation) withdraw 5–20 times and consume nearly 2–5 times more water than by using petroleum gasoline. The water intensities (gal H_2O/mile) of LDVs operating on biofuels derived from crops irrigated in the United States at average rates is 28 and 36 for corn ethanol (E85) for consumption and withdrawal, respectively. For soy-derived biodiesel the average consumption and withdrawal rates are 8 and 10 gal H_2O/mile.

1. Introduction

In this paper we discuss the water intensity, or water consumption and withdrawal, related to the production and use of transportation fuels within the United States. This information provides insight into the policy discussion regarding which alternative fuels are most appropriate for the U.S. as a whole as well as regional subsets of the U.S. That is to say, given the variable climate and geology of different regions of the U.S., the same fuel may be more appropriate to produce in one part of the country versus another in terms of its water intensity.

We discuss the *water usage per mile driven* for light duty vehicles (LDVs), which include cars, trucks, and sport utility vehicles (SUVs), to formulate the result on the consumer and policy levels. Over 97% of the 2.7 trillion miles Americans drove in 2005 were fueled by petroleum-derived gasoline and diesel, which is now commonly being mixed with up to 10% ethanol as a replacement for methyl tertiary-butyl ether, or MTBE, in reformulated gasoline (*1*, *2*). Thus, to project the water quantities used for driving on various fuels, one simply needs to multiply the results of this paper by a target number of miles.

1.1. Defining *Consumption* and *Withdrawal* of Water. Understanding the difference between water *consumption* and *withdrawal* is important when planning with regard to water usage.

Water ***consumption*** describes water that is taken from surface water or groundwater source and not directly returned, for example, a closed-loop cooling system for thermoelectric steam power generation where the withdrawn water is run through a cooling tower and evaporated instead of being returned to the source is consumption.

Water ***withdrawal*** pertains to water that is taken from a surface water or groundwater source, used in a process, and given back from whence it came to be available again for the same or other purposes. An example is an open-loop cooling system for thermoelectric steam power generation that pumps cool water from a reservoir into its condensing unit and discharges the majority of that heated water back into the reservoir where any water not evaporated due to the added heat is withdrawn. For any given water withdrawal, consumption is less than or equal to the amount withdrawn.

1.2. Accuracy of Analysis. Performing the analysis of this paper inherently relies on the accuracy of the referenced data. Thus, we have no specific tolerance or uncertainty associated with our calculations for gallons of water per mile. In some cases we have a range of values; in others we have only a typical, or average, value. For example, the amount of water consumed for irrigating corn varies depending upon geographic location so we present a range of values. The calculations are generally accurate to two significant digits. A comprehensive sensitivity analysis is difficult to conduct given the varying type of units and factors involved for comparing water usage for different fuels and technologies. Section 3.3 presents a brief sensitivity analysis varying some of the more influential factors.

2. Experimental Procedures

2.1. Water Usage for Automotive Fuels - Methodology. In this section we show the results of well-to-wheel (or field-to-wheel, as the case may be) analyses that calculate water consumption and withdrawal for fuel production and usage in propelling LDVs. The calculation of water consumption and withdrawal to propel a light duty vehicle follows a similar approach for each fuel. We considered the following three major factors affecting water usage: mining and farming of feedstock, processing and refining of feedstock to fuel, and efficiency of use of fuel in vehicle (see Figure 1).

Mining and farming relate to the means for accumulating the feedstock for the end fuel. Processing and refining are then required to turn the feedstock into the final fuel used in a vehicle. The efficiency with which the vehicle can use the fuel is the final factor affecting how much water is used to propel the vehicle. The vehicle fuel efficiency is defined as the distance the LDV can travel on a unit of fuel. Detailed calculations are shown in theSupporting Information Ap-

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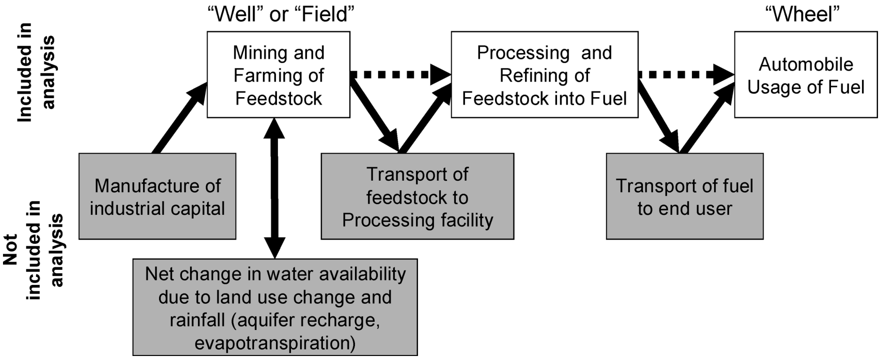

FIGURE 1. Included in our well-to-wheel or field-to-wheel analysis are the mining/farming and refining/processing of feedstock plus the efficiency of usage of the fuel in an automobile. We neglect the water usage involved in the manufacture of industrial capital, the transport of feedstock and fuels, and farming and irrigation effects upon aquifers. The dashed lines indicate the flows of the analysis of this paper, while the solid lines indicate the true physical flows.

pendix S-A for water consumption and Appendix S-B for water withdrawal.

We neglected four categories of water usage in this analysis: 1. *Transport of feedstock from mine/farm to refinery*; 2. *Transport of refined fuel to consumer purchase point*; 3. *Manufacturing and installation of physical capital*; and 4. *Water availability (aquifer recharge, river flow, evapotranspiration) for biofuel crops*.

The reason for neglecting the first two items relates to transport, which also requires a fuel in itself. We decided not to include analysis of an automotive fuel to transport itself versus using one of the other fuels or nonvehicle related transport mechanisms (e.g., pipelines). The inclusion of transport can only add to the water intensity of transportation fuels. However, we did consider water usage for pipeline transport of natural gas and electricity transmission because the infrastructure has been in place for many years for purposes other than automotive travel.

Also, the manufacturing and installation of the physical capital associated with mining, farming, transport, and manufacture of fuel infrastructure were neglected as this physical capital often has many other purposes. For example, the national electric grid is already ubiquitous even without electric vehicles using it to charge batteries. Because physical capital can be reused over many years, we anticipate a negligible water usage contribution from this category.

Past researchers (*3*) have quantified the evapotranspiration (ET) of biofuel crops to quantify global water requirements. While important as measures, we neglected the consideration of rainfall and evapotranspiration (ET) for biofuel crops, because the effects are inherently regional and need to be discussed in the context of regional water sustainability. Scanlon et al. (*4*) point out that ET and net water flux on agricultural lands can be greater or lesser depending upon the alternate land use and agricultural practices including tillage and fallow periods. Thus, depending upon alternate land uses compared to biofuel crops, we cannot speculate if biofuel crops will have more or less impact on the regional water supply.

Regional water supply sustainability within the hydrologic cycle connecting rainfall, ET, aquifer recharge, streamflow, land use, and land cover is outside the scope of this manuscript. We have simply chosen to model direct human actions on water usage from concentrated sources (e.g., lakes, rivers, and aquifers). By including ranges of irrigation quantity with the resulting crop yields, we inherently include some link between regional crop ET and rainfall to inform decision making.

2.2. Water Usage - Conventional Petroleum Gasoline and Diesel. We have described elsewhere the method used to calculate water usage for propelling LDVs on gasoline (*5*). The values in ref *5* were based primarily upon the values of Gleick stating that oil refining consumes 1−2.5 gallons of water per gallon of refined product and withdraws approximately 12.5 gallons per gallon of refined product (*5, 6*). Most of the water withdrawn is for cooling of electricity generating equipment in refineries, and consumption is primarily a result of refinery process cooling and domestic enhanced oil recovery methods. We assume the water use for the mining and refining of diesel is the same as for gasoline.

The vehicle fuel efficiency in "miles per gallon of fuel" (mpg) is 20.5 mpg for gasoline LDVs as described in ref *6* for a vehicle fleet composed of 60% cars and 40% light trucks and SUVs. Because diesel LDVs use both a fuel with higher energy content than gasoline and engines with a different design, they have a higher fuel efficiency than that for gasoline LDVs. To estimate the increase in mpg rating for diesel LDVs over that of gasoline we compared vehicle models that are the same or very similar and that have both diesel and gasoline versions (*7, 8*). Diesel LDVs had an average 1.38 times better fuel efficiency than gasoline or 28.2 mpg (error due to rounding) (see the Supporting Information Appendix S-A).

Our results show that driving a petroleum gasoline-fueled LDV typically consumes between 0.07−0.14 gal H_2O/mile as compared to 0.05−0.11 gal H_2O/mile for a petroleum diesel-fueled LDV. The water withdrawal is approximately 3−4 times as high at 0.63 gal H_2O/mile and 0.46 gal H_2O/mile for gasoline and diesel, respectively.

2.3. Water Usage - Oil Shale and Tar Sands to Gasoline. Oil shale and tar sands present one of the more direct substitutions for conventional petroleum and are often placed into a category of fossil resources called 'unconventional oil'. Usually, the 'unconventional' nature of these sources pertains to the fact that the petroleum reserve requires considerably more input energy and materials (e.g., CO_2, water/steam, electricity, heat, digging) to mine and/or process the fuel.

Oil shale and tar sands require water either to extract them from the ground using in situ processes or by processing after conventional surface or underground mining (*9*). Past efforts at oil shale extraction have ceased partially because of large water demands in areas where resources are already strained (*10*). Nonetheless, the public literature (*11*) points to possible technological improvements that reduce the usage of water by over half−or use no water at all for certain deposits.

Without considering future technological reductions in water usage, mining and retorting of oil shale and tar sands consumes a large amount of water at 2−5 gal water/gal oil for oil shale (*10*) and 3−7 gal water/gal oil for tar sands (*12*). These values result in water consumption for converting oil shale to gasoline for use in LDVs to be 0.15−0.37 gal H_2O/mile. For tar sands the water consumption is calculated a little higher, at 0.20−0.46 gal H_2O/mile. This higher value is due to more water intensive mining based upon practices in the Athabasca River Basin in Canada. In calculating the water withdrawal for using oil shale and tar sands converted to gasoline to power LDVs, we add the additional water consumption for mining to the water withdrawal amount used for petroleum refining. This addition results in water withdrawal rates of 0.71−0.86 gal H_2O/mile for oil shale and 0.76−0.95 gal H_2O/mile for tar sands.

2.4. Water Usage - Coal and Natural Gas to Fischer−Tropsch Diesel. Coal and natural gas can be converted to liquid fuels to substitute for petroleum. While the U.S. has an abundant supply of coal reserves, U.S. natural gas production has declined since the beginning of this century (*13*) and imports are increasing by way of liquefied natural gas (LNG). As time passes LNG may become a fungible global commodity much as oil is today making it a viable feedstock for transportation fuel in LDVs even if imported. The technology for converting hydrocarbons into Fischer−Tropsch (F-T) fuels is well established. The feedstock is converted into a syngas, composed primarily of hydrogen (H_2) and carbon monoxide (CO), which is then processed with steam to form liquid diesel. In developing syngas, coal must be gasified from its solid form, whereas natural gas must have its hydrogen stripped from its carbon using steam methane reforming or autothermal reforming. The syngas is then processed in a F-T reactor to form liquid fuel.

The water consumption for converting coal and natural gas to F-T diesel travel in LDVs is 0.19−0.58 gal H_2O/mile and 0.12−0.43 gal H_2O/mile, respectively. The lower values for natural gas to F-T liquids is intuitive because conventional natural gas consumes almost no water in mining and processing for pipeline transport, whereas mining coal can consume water for dust suppression and cleaning (*6, 10*). Also, coal must be gasified which requires addition of steam. The water withdrawal for coal and natural gas to F-T diesel is essentially the same as consumption because most water is used for processing the syngas. A negligible amount is used for cooling which is the usual cause for withdrawal to be higher than consumption in industrial processes. Additionally, as unconventional gas resources, such as shale gas and tight sands, are produced, the water intensity of its production can increase as high-pressure water streams are used to fracture the shale (*14*). This 'fracing' water usage has been included (also for compressed natural gas LDVs) into mining for natural gas, but it contributes negligibly (~0.01 gal H_2O/mile).

2.5. Water Usage - Electricity − Electric Vehicles and Plug-in Hybrid Electric Vehicles. The water consumption and withdrawal for an electric vehicle (EV), and also for a plug-in hybrid electric vehicle travel (PHEV) in electric mode, was calculated in a previous publication (*5*). We refer the reader to that publication for a full discussion of water usage for electric LDV travel.

A value of 0.37 kWh/mile was used for average electric vehicle efficiency that includes an overall charger, battery, and transmission and distribution efficiency of 68%. Water used for extraction of electricity fuels and cooling of steam-electric power plants caused the U.S. average electric mix to consume water at 0.465 gal/kWh and withdraw water at 21.4 gal/kWh. Thus, PHEVs were calculated to consume and withdraw water at 0.24 gal H_2O/mile and 7.8 gal H_2O/mile, respectively, during electric travel. Note that if the electric travel is powered by electricity generated from sources that do not directly use water, such as wind power and photovoltaic solar, there is no water usage as calculated in this paper.

2.6. Water Usage - Hydrogen Fuel Cell. Here we explore operating a fuel cell vehicle (FCV) on hydrogen that is derived from steam methane reforming (SMR) of natural gas or electrolysis using electricity from the average U.S. grid mix. We assume a 60% efficiency fuel cell (*15*) along with the same electricity-to-wheel efficiency of 0.25 kWh/mile as for electric vehicles (for electricity out of the battery). Since FCVs and EVs/PHEVs both operate on electric drives and will likely not significantly differ in size, shape, and weight, we see the fuel economy assumption as reasonable.

Hydrogen from Natural Gas. The Department of Energy estimates that approximately 4.5 gallons of water are consumed per kilogram of H_2 produced from natural gas via SMR (*10*). About 1 gallon of this water is used as feedstock, and the rest is consumed as steam. Withdrawal of water is only slightly more than consumption at 4.9 gal H_2O/kg H_2 (*10*). These values equate to a per mile water usage of 0.06 and 0.07 gal H_2O/mile for consumption and withdrawal, respectively.

Hydrogen from Water via Electrolysis. Compared to SMR, obtaining hydrogen from water via electrolysis requires water as feedstock and electricity as an energy input (*16*). The amount of hydrogen in water is 2.38 gal H_2O/kg H_2, and using an energy equivalence of 33.33 kWh/kg H_2 we calculate 0.03 gal H_2O/mile is consumed as feedstock for hydrogen.

The overall efficiency of the electricity (prehydrogen) to electricity (output from fuel cell) for the FCV is assumed at 43% (*15*). Using the same water usage values for electricity generation as stated in the earlier EV/PHEV section produces water consumption at 0.42 gal H_2O/mile and withdrawal at 13 gal H_2O/mile. Note that if nonsteam renewable electric generation was used to perform the electrolysis, only the water as feedstock would be consumed and withdrawn (0.03 gal H_2O/mile).

2.7. Water Usage - Natural Gas Combustion − Compressed Natural Gas (CNG). While natural gas vehicles (NGVs) are not currently widespread in the U.S., this could change in the future. Worldwide there are approximately 7 million NGVs, with 150,000 in the U.S. (*17*). Additionally, carmakers are making fewer NGVs for the U.S. market, not more, as only one commercial NGV 2008 model, the Honda Civic, compared to 15 commercial NGVs in 2000 (*7, 18*).

The equivalent miles per gallon for NGVs is approximately the same as for gasoline vehicles as some NGVs operate both below and above the efficiency of the equivalent gasoline LDV model. We assumed an energetic fuel efficiency for NGVs equal to that used for gasoline (121.5 ft^3 natural gas = 1 gallon of gasoline) (*7*). The LDV mileage per standard cubic feet (SCF) of natural gas used calculates to 0.17 miles/SCF or 5.9 SCF/mile.

Natural gas compressors are powered by electricity or natural gas itself. The electricity required for compressing natural gas to 4000 psi ranges from about 0.01−0.016 kWh/SCF (*19*). We use a natural gas compressor efficiency of 91.7% where 8.3% of the gas powers the compressor, and the rest is put into the CNG tank (*19*).

When using electrical compressors, 0.06−0.10 kWh/mile is required for natural gas compression. The resulting water usage for electricity from the U.S. grid mix is 0.06−0.07 gal H_2O/mile consumption and 1.3−2.1 gal H_2O/mile withdrawal. If using natural gas-powered compressors, approximately 6.5 SCF/mile of gas is used for compressing the natural gas, and the resulting water usage is approximately 0.03 gal H_2O/mile for both consumption and withdrawal.

2.8. Water Usage - Biofuels − Ethanol (E85) driving from Corn Grain Starch and Cellulosic Corn Stover. In evaluating the water consumed and withdrawn for ethanol, we assume that ethanol can be produced from corn seed (e.g., grain) and/or corn stover and that LDVs run on fuel that is 85% ethanol and 15% gasoline (E85). We have factored coproducts into the overall corn grain ethanol process with the allocation factors from the ethanol process comparisons in ref *20* by assuming that these factors represent the water usage associated with ethanol. These allocation factors for the six studies are 65%−93% and represent the fraction of the life cycle energy allocated to ethanol versus the coproducts (e.g., dry distillers grain) (*20*). Based upon the aboveground dry matter ratio of stover:grain in ref *21*, we assume the water allocation factor for ethanol from corn stover is 54% when using the corn grain for food. Differences in process water can be visualized from the plots showing nonirrigated ethanol.

In addition to the cellulosic material in corn stover, lignin is also a major component that is separated. Because enough electricity can be produced from combustion of the lignin from corn stovers, all electricity at the assumed corn stover ethanol processing plant is assumed from this source (*20*).

The major water consumption area for terrestrial biofuel crops is the water used to actually grow the plant whether via irrigation or rainfall. Irrigation for growing corn varies substantially across the U.S. Using USDA irrigation data we calculate a range of water usage for growing corn based upon statewide data (*22*). The low and high ends of the range are dictated by the minimum and maximum quantity of "bushels/ac-ft": irrigation (acre-ft/acre/yr) divided by yield (bushels/acre). Irrigation water consumption is smaller than withdrawal based upon statewide percentages given by the United States Geological Survey (*23*) (see the Supporting Information).

Water consumed for farming energy usage is small compared to irrigation at 0.11 gal H_2O/gal ethanol, and it includes water consumed to make the gasoline, diesel, and electricity used during farming (*24*). We neglected the water required to make fertilizers.

Because the ethanol chemical processing is different for making ethanol from corn grain versus from corn stover, the water usage is also different. Data from Minnesota ethanol refineries show that water consumption lies in a range of 3.5−6.0 gal H_2O/gal ethanol for ethanol from corn grain, usually using dry-milling methods (*25*). The National Renewable Energy Laboratory calculated that approximately 7.3 gal H_2O/gal ethanol would be consumed for a processing plant designed to use corn stovers (*26*).

In surveying statistics of three cars and five trucks/SUVs that have gasoline and E85 versions, we discovered the rated vehicle fuel efficiency, by volume in "miles per gallon" (mpg), was reduced by approximately 26% for E85 versus gasoline. From this volumetric fuel efficiency decrease we calculate a composite E85 fuel efficiency of 15.1 mpg. The data for our E85 fuel efficiency calculation are shown in the Supporting Information Appendix S-A as listed by the U.S. government Web site www.fueleconomy.gov (*7*).

Assume Only Ethanol Is Only from Corn Grain. If ethanol is processed from corn grain in irrigated fields, then water consumption is 1.3−62 gal H_2O/mile (average of 28 gal H_2O/mile) and withdrawal is 6.9−110 gal H_2O/mile (average of 36 gal H_2O/mile). Ethanol processed from corn grain from nonirrigated fields results in water consumption and withdrawal intensities of 0.15−0.35 gal H_2O/mile and 0.33−0.56 gal H_2O/mile, respectively.

Assume Only Ethanol Is Only from Corn Stover. If ethanol is processed from corn stover in irrigated fields, then water consumption is 2.6−46 gal H_2O/mile (average of 19 gal H_2O/mile) and withdrawal is 5.6−63 gal H_2O/mile (average of 23 gal H_2O/mile). Ethanol processed from corn stover from nonirrigated fields results in water consumption and withdrawal intensities comparable to corn grain at 0.25 gal H_2O/mile and 0.41 gal H_2O/mile, respectively.

Assume Ethanol Is from Corn Grain and Corn Stover of the Same Plant. If we assume that ethanol is made from the corn grain and corn stover from the same plant, then the water used in irrigation is split between the two feedstocks. Approximately double the ethanol is produced from the same corn plant, thus lowering the water usage for fuel even further.

The above ground mass ratio of dry corn stover to wet grain during harvest time is about 0.75−0.83, and the dry matter split between corn stover and grain is roughly 54% stover and 46% grain, giving a 1.17 dry stover:grain ratio (*21*). By factoring this ratio into the amount of ethanol from an equivalent dry bushel of corn (i.e., the stover mass associated from a bushel of corn grain), we calculate that 6.2 gallons of ethanol result from one equivalent grain bushel. This split approximately halves the consumption and withdrawal of water for E85-powered LDV travel to 1.6−38 gal H_2O/mile (11 gal H_2O/mile average) and 3.4−51 gal H_2O/mile (16 gal H_2O/mile average), respectively. The water intensity for E85 using stover and grain from the same nonirrigated corn plant is comparable to using grain or stover only as the consumption and withdrawal rates are 0.22−0.38 gal H_2O/mile and 0.41−0.56 gal H_2O/mile, respectively.

2.9. Water Usage - Biofuels − Soy Biodiesel. Biodiesel processing technology is mature and can be integrated relatively well into existing infrastructure to substitute for petroleum diesel. Based upon different higher heating value (HHV) energy content values for petroleum diesel (138,700 Btu/gal - HHV) versus biodiesel (126,206 Btu/gal - HHV), we assume a LDV running on biodiesel has a proportionally lower fuel efficiency of 25.7 mpg (*27*).

Just as with corn-based ethanol, if soybeans are irrigated, then that irrigation dominates the water consumption and withdrawal. Soy irrigation ranges from 0.2−1.9 acre-ft/acre/yr, and the average soybean irrigation across the U.S. is 0.8 acre-ft/acre/yr (*22*). Across the world there are other plants and seeds that are used as feedstock for biodiesel, such as palm oil in Southeast Asia, but soybeans are a major feedstock in the U.S. Allocation factors vary widely in life cycle analyses of biodiesel from soybeans, and a range of 0.18−0.80 was used with an assumed average in the middle (*28*).

Biodiesel derived from irrigated soybean fields has water consumption of 0.6−24 gal H_2O/mile (average of 8 gal H_2O/mile) and withdrawal of 1.1−26 gal H_2O/mile (average of 10 gal H_2O/mile). If the soy fields are not irrigated, then just as with ethanol, the consumption and withdrawal are 2 orders of magnitude less at 0.01−0.02 gal H_2O/mile and 0.03−0.12 gal H_2O/mile, respectively.

3. Results and Discussion

3.1. Water Intensity for LDV Fuels. Figure 2 presents results for consumption and withdrawal (gal H_2O/mile) for the fuels studied in this paper. Figure 2 is useful for easily comparing the magnitude of water intensity for each fuel.

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. The lowest water consumptive and water withdrawal rates are for LDVs using conventional petroleum-based gasoline and diesel, nonirrigated biofuels, hydrogen derived from methane/natural gas, and electricity derived from renewable and nonsteam based generation. LDVs powered by the aforementioned fuels consume less than 0.15 gal H_2O/mile and withdraw less than 1 gal H_2O/mile.

Due to water cooling, LDVs running on electricity and hydrogen derived from fossil fuel and nuclear steam-electric power generation withdraw 5−20 times more water and consume nearly 2−5 times more water than by directly using fossil fuels. LDVs operating on irrigated biofuels consume and withdraw 1−3 orders of magnitude more water per mile than traditional petroleum based gasoline and diesel as the intensity varies greatly on regional irrigation patterns.

3.2. Sensitivity Analysis. A sensitivity analysis was performed using four of the most influential factors in the water intensity calculations: vehicle fuel economy, water usage for electricity generation (gal/kWh), crop yield, and irrigation quantity (see Table 1). Obviously the last two factors only

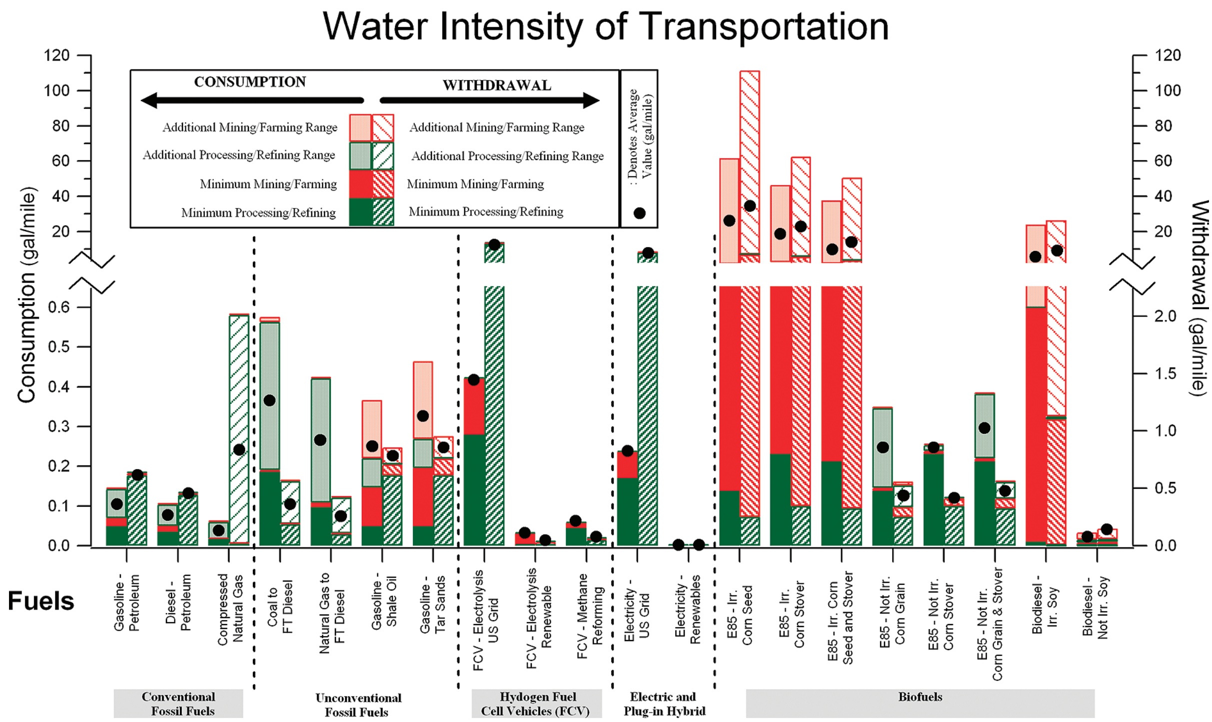

FIGURE 2. Water consumption (*left stacked bars* read on *left axis*) and withdrawal (*right stacked bars* read on *right axis*) in gallons of water per mile (gal/mile) for various fuels for light duty vehicles. Water use from mining and farming is designated differently from that used for processing and refining. Where a range of values exists (e.g., different irrigation amounts in different states), a minimum value is listed with an 'additional range'. Otherwise, the values plotted are considered average values. Irr. = irrigated, Not Irr. = not irrigated, FT = Fischer–Tropsch, FCV = fuel cell vehicle, U.S. Grid = electricity from average U.S. grid mix, and Renewables = renewable electricity generated without consumption or withdrawal of water (e.g., wind and photovoltaic solar panels).

TABLE 1. Results of Sensitivity Analysis in Units of Gal H_2O/Mile per Percentage (Whole Number) Change[a]

	Consumption (gal H2O/mile)				Withdrawal (gal H2O/mile)			
	% change in LDV fuel economy	% change gal/kWh for electricity	% change in crop yield	% change in irrigation	% change in LDV fuel economy	% change gal/kWh for electricity	% change in crop yield	% change in irrigation
Gasoline - Petroleum	-7.1E-4	NI	--	–	-4.2E-3	NI	–	–
Diesel - Petroleum	-5.2E-4	NI	--	–	-3.1E-3	NI	–	–
Compressed Natural Gas	-3.4E-4	3.6E-4	--	–	-6.8E-3	1.0E-2	–	–
Coal to FT Diesel	-2.6E-3	NI	--	–	-2.6E-3	NI	–	–
NG to FT Diesel	-1.8E-3	NI	--	–	-1.8E-3	NI	–	–
Gasoline (oil shale)	-1.7E-3	NI	--	–	-5.2E-3	NI	–	–
Gasoline (tar sands)	-2.2E-3	NI	--	–	-5.7E-3	NI	–	–
H2 - Electrolysis U.S. Grid	-4.2E-3	2.8E-3	--	–	-1.3E-1	1.3E-1	–	–
H2 - Electrolysis Renewables	-3.0E-4	0.0E+0	--	–	-3.0E-4	0.0E+0	–	–
H2 - SMR	-5.6E-4	0.0E+0	--	–	-7.3E-4	0.0E+0	–	–
Electricity - U.S. Grid	-2.4E-3	1.7E-3	--	–	-7.8E-2	7.7E-2	–	–
Electricity - Renewables	0.0E+0	0.0E+0	--	–	0.0E+0	0.0E+0	–	–
E85 - Irr. Corn Seed	-2.6E-1	1.8E-5	-5.2E-1	3.9E-1	-2.1E-1	6.6E-4	-4.2E-1	3.1E-1
E85 - Irr. Corn Stover	-1.7E-1	1.2E-5	-3.3E-1	2.5E-1	-1.7E-1	5.5E-4	-3.3E-1	2.5E-1
E85 - Irr. Corn Seed and Stover	-9.6E-2	1.5E-5	-1.9E-1	1.4E-1	-9.7E-2	6.6E-4	-1.9E-1	1.4E-1
E85 - No Irr. Corn Seed	-1.6E-3	1.8E-5	0.0E+0	0.0E+0	-1.5E-3	8.1E-4	0.0E+0	0.0E+0
E85 - No Irr. Corn Stover	-1.6E-3	1.2E-5	0.0E+0	0.0E+0	-2.8E-3	5.5E-4	0.0E+0	0.0E+0
E85 - No Irr. Corn Seed and Stover	-2.0E-3	1.8E-5	0.0E+0	0.0E+0	-3.2E-3	6.6E-4	0.0E+0	0.0E+0
Biodiesel - Irrigated Soy	-1.5E-1	0.0E+0	-3.1E-1	2.3E-1	-1.6E-1	0.0E+0	-3.1E-1	2.3E-1
Biodiesel - Non-irrigated Soy	-1.9E-4	0.0E+0	0.0E+0	0.0E+0	-1.2E-3	0.0E+0	0.0E+0	0.0E+0

[a] E.g. a 10% increase in LDV fuel economy results in a water consumption reduction of 2.6 gal/mile for E85 from irrigated corn seed. NI = either not included in analysis or not explicitly included in calculations. - = not applicable.

relate to biofuels. For the sensitivity analysis, relative changes were employed because of the diversity of units in comparing fuels with different units and energy content even with the same units (e.g., kWh, gallons of gasoline, cubic foot of natural gas, etc.).

No results from the sensitivity study are unexpected. Fuel economy and irrigation have the largest impact upon vehicles using fuels that use the most water (e.g., irrigated biofuels). Because irrigation dominates all water usage categories for irrigated biofuels, relative changes in irrigated water, due to allocation factor (i.e., methodology) or regional irrigation patterns, result in the almost exact proportional changes in water usage. Changes in electricity usage affect water usage of vehicles that most directly use electricity: electric and plug-in vehicles, fuel cell vehicles obtaining hydrogen via electrolysis, and natural gas vehicles using electric compressors. Adjusting crop yield relates only to irrigated biofuels as the processing and refining of feedstocks is by definition not a factor of farming yields because evapotranspiration was neglected.

3.3. Conclusions and Policy Implications of Water Intensity for LDV Fuels. Transportation is yet another area where the nexus between water and energy can potentially create conflicts where they did not exist before. This paper provides a broad overview of the water intensity of various transportation fuels by putting the results in the context of the consumer—in gallons of water consumed/withdrawn per mile traveled. Much as LDV fuel economy is listed as miles per gallon and municipal water use is quoted in gallons per capita, our measure provides a way for people to compare their behavior and to help track the trade of water that is embedded in the fuels consumed throughout the country. By multiplying the number of miles driven on each particular fuel by the water intensity in "gal H_2O/mile" we can estimate the total water quantities used for transportation.

The historical use of petroleum-based fuels has had a small overall impact upon U.S. water resources, and the most plausible alternatives have higher water intensities. Moving to other fossil resources (coal, shale oil, tar sands), other than natural gas, to make liquid fuels approximately doubles the water consumption intensity, and the water used will likely be from inland sources where fresh water is already scarce.

The difference in water intensity between irrigated and nonirrigated biofuel feedstocks (up to 3 orders of magnitude in gallons per mile) shows the tremendous amount of need to properly plan for their incorporation. Due to water resource limitations at aquifers that are already being used intensively for food crop production, using those same aquifers for fuel production may exceed existing limits. The enhanced use of biofuel crops that need less water and the organized planting of crops in water and rain rich areas can lessen the water impact of biofuels.

The water impact from using hydrogen and electricity to power LDVs can vary substantially, from no water usage if using renewable energy sources that do not use water at all to 2−5 times as much consumption per mile and 11−17 times as much withdrawal per mile if the average U.S. electric grid mix is used to charge electric vehicles or for electrolysis to generate hydrogen. Using hydrogen derived from natural gas has among the lowest water intensities.

Making decisions while only considering aggregate water consumed and withdrawn on the basis of a region as large as the United States is too simplified. In practice regional impacts will dictate the successful implementation of any of the discussed fuels for LDV travel. Example regional impacts range from relatively localized around shale oil mining and coal to liquids refining to larger agricultural regions used to grow biofuel crops. Future work needs to show the viable areas of the U.S. where each fuel can be mined, farmed, refined, and consumed to minimize the regional impacts while maximizing broad economic and policy objectives that include water resource and energy sustainability. Where possible, the use of low-quality water sources, such as saline or reclaimed waters, can minimize the quantity of fresh water impact from most of the fuels included in this study. Policy makers should be aware that, due to the inherent distribution of water (through geology and weather), fossil, and natural resources, each state or region may not be able to contribute to the production of future transportation fuels in the same manner.

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Supporting Information Available

Table of energy densities for fuels analyzed; calculations used to derive the final values for water consumption and withdrawal for LDV travel; and references for sources used in calculations but not explicitly noted in main text. This material is available free of charge via the Internet at http://pubs.acs.org.

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