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The water needs for LDV transportation in the United States

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ABSTRACT

Concern over increased demand for petroleum, reliable fuel supply, and global climate change has resulted in the US government passing new Corporate Average Fuel Economy standards and a Renewable Fuels Standard. Consequently, the fuel mix for light duty vehicle (LDV) travel in the United States will change over the coming years. This paper explores the embodied water consumption and withdrawal associated with two projections for future fuel use in the US LDV sector. This analysis encompasses conventional and unconventional fossil fuels, corn ethanol, cellulosic ethanol, soy biodiesel, electricity, and hydrogen. The existing mandate in the US to blend ethanol into gasoline had effectively committed 3300 billion liters of irrigation water in 2005 (approximately 2.4% of US 2005 fresh water consumption) for producing fuel for LDVs. With current irrigation practices, fuel processing, and electricity generation, it is estimated that by 2030, approximately 14,000 billion liters of water per year will be consumed and 23,000–27,000 billion liters withdrawn to produce fuels used in LDVs. Irrigation for biofuels dominates projected water usage for LDV travel, but other fuels (coal to liquids, oil shale, and electricity via plug-in hybrid vehicles) will also contribute appreciably to future water consumption and withdrawal, especially on a regional basis.

1. Introduction

Increases in demand for petroleum have put a strain on global petroleum supply. The former Chief Executive of Shell, Jeroen van der Veer, suggested that by 2015 global oil and gas production will no longer keep up with demand (van der Veer, 2008). In addition, there are political concerns about global climate change and a desire for increased production of domestic fuels. Consequently, governments and companies are turning to alternative fuels to replace petroleum products, reduce greenhouse gas emissions, and reduce fuel imports. These alternative fuels range from syn-fuels (such as coal to liquids or CTL), to renewable biofuels and electricity for plug-in hybrid electric vehicles. However, many of these alternative fuels are more water intensive than conventional petroleum-based sources. The use of water for their production will increasingly be in competition with municipal and industrial uses as well as electric power and food production. This paper presents estimates of the water consumption and withdrawal that would result from the exploitation of a diverse set of alternative automotive fuels within the United States.

The term water *usage* has been used in many different senses by various authors. For the sake of clarity and consistency, this paper will use the terms *consumption* and *withdrawal*. Water *withdrawal* pertains to the quantity of water that is taken from a lake (or other surface or groundwater source), and used in a process. Usually processes that have high withdrawal nominally return most water (minus the portion that is consumed) to the original source to be available for the same or other uses. An example is an open-loop cooling system for thermoelectric steam power generation. Such a system withdraws cool water from a river into its condensing unit and discharges the water (less some consumption) back into the river. Water *consumption* refers to quantity of water that is withdrawn from surface water or groundwater source and not returned to the source. For example, in a closed-loop cooling system for thermoelectric steam power generation a portion of the withdrawn cooling water is evaporated in a cooling tower or from the surface of a recirculating cooling reservoir after being raised to an elevated temperature. For any given water withdrawal, consumption is always less than or equal to the amount withdrawn. Water consumption is of particular concern when it occurs in areas that already have scarcity issues or are near the limits of sustainability.

This study considers light duty vehicle (LDV) travel in the US driven by cars, pickup trucks, vans, and SUVs. The analysis is based on the 2008 Annual Energy Outlook (AEO) reference

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projection of fuel consumption published by the Energy Information Administration (EIA) of the US Department of Energy (DOE) (EIA, 2008), which includes nominal adoption of fuels and technologies. Additionally a progressive alternative fuel projection derived by the National Energy Technology Laboratory (NETL) to achieve a model for "advantageous interdependence" is used (Kern et al., 2007). The analysis presented herein is dependent on both these projections of future fuel usage and incorporates policy changes from the Energy Independence and Security Act of 2007 (EISA, 2007). The model uses previously published calculations of water usage rates in volume of water per distance driven (i.e. "gallons H_2O per mile or liters H_2O per kilometer) using various fuels (King and Webber, 2008a). Converting projected fuel usage (units of fuel) into kilometers driven and then multiplying by water usage rates per km yields an estimate of the total water consumed and withdrawn for driving LDVs. This approach provides the interested consumer with an estimate of embodied water consumed and withdrawn for driving.

The analysis is also scaled up for the entire United States. The Appendix provides some background knowledge that is the basis for the fuel projections. This background includes descriptions of the AEO and NETL fuel projections (Section A.1) and how fuel consumption is converted into km (Section A.3). Section A.2 illustrates the inclusion of renewable fuels standards (RFS). Special attention is given to some biofuels (cellulosic and gasified) that were not analyzed in previous work (Section A.3).

2. Water for biofuels consumed in LDVs

The use of irrigation water is a major contributing factor to the water intensity of biofuels. To assess irrigation water quantities the data from the United States Department of Agriculture (USDA) Irrigation Survey (USDA, 1998 and 2003) and National Agricultural Statistics Service (NASS) are used (NASS, 2008). In 2003, approximately 1.7 billion out of 10.1 billion bushels (17%) of corn grain were irrigated. Also 257 million out of 2454 million soy bushels (10%) were irrigated. While it is not clear whether future biofuels crops will have a higher or lower fraction of irrigation than present day grain production, these quantities are used to apportion irrigated and non-irrigated ethanol (from corn) and biodiesel (from soy). No cellulosic crops have yet to be specifically grown for biofuels. Although an unknown fraction of cellulosic ethanol will be produced from waste wood from forests and the lumber industry, we assume that ethanol made from cellulosic materials will have the same irrigated ratio by mass as it does for corn. This assumption may overestimate future water consumption because of the possibility that a smaller fraction of cellulosic feedstocks will be irrigated. However it is also possible future prices for biofuels crops may drive more irrigation as a way to increase yields.

For all irrigated US corn in 2003, the average irrigation withdrawal equates to 2970 L H_2O/L ethanol translating to an average of 82 L H_2O/km (from 15 to 260 L H_2O/km depending upon which state the corn is grown) when weighted as E85 and accounting for the fuel efficiency of the vehicle (King and Webber, 2008b; USDA, 1998 and 2003). For all irrigated US soy beans, the average irrigation withdrawal equates to 590 L H_2O/L biodiesel translating to an average of 24 L H_2O/km (King and Webber, 2008b; USDA, 1998 and 2003). In determining how much irrigation water is consumed versus withdrawn, this analysis uses the United States Geological Survey (USGS) estimate of 20% of irrigated water being returned to the source (Solley et al., 1998). This withdrawal/consumption ratio for irrigation greatly varies depending upon the irrigation techniques used in particular regions with many regions having 0% of irrigation water returned to the source. Nonetheless, this broad measure was used as it allows comparison to past USGS statistics.

One previous unknown was the water intensity for ethanol made from future cellulosic materials that could include forest waste, switchgrass, and sorghum (or possibly imports if trade policies are changed). For cellulosic ethanol, our previous work used a modeling study performed by the National Renewable Energy Laboratory (NREL) for an ethanol plant using corn stover as a feedstock (King and Webber, 2008b; Aden et al., 2002). Some small amount of cellulosic ethanol production from corn stover is assumed. The water consumption and withdrawal rates for processing and refining corn grain and stover were somewhat different at 3.5–6.0 L H_2O/L ethanol for corn grain and 7.3 L H_2O/L ethanol for corn stover (Aden et al., 2002). Also, an equivalent bushel (56 lbs) of both corn grain and stover produce approximately 10.6–11.4 L of ethanol.

The larger unknown for the consideration of future water usage regarding cellulosic biofuels is the amount of *irrigation* water used per mass of an array of cellulosic biomass feedstocks. Some believe that many of the future biofuels will be grown on less desirable land than currently used and consist of less water intensive varieties that do not require irrigation. Others argue that the prices for biofuel feedstocks could justify the use of substantial irrigation water for the production of the most biomass per acre. At this time it is unclear which combination of cellulosic feedstocks will be used. For our analysis, we assume that similar irrigation patterns to corn will continue for future general cellulosic feedstocks, and unless specified otherwise, that cellulosic biomass grown for contributions to the RFS will be converted to ethanol as opposed to another fuel (e.g. burned for electricity).

The general cellulosic biomass characteristics assumed are that approximately 310 L of ethanol can be produced per dry tonne of biomass (switchgrass) at 80% conversion from theoretical maximum (DOE, 2009). The average irrigation quantity when irrigating cellulosic crops is assumed as 3.7 ML/ha (same as corn) (USDA, 1998 and 2003) with 17% of the cellulosic biomass for ethanol assumed irrigated (same as corn). The water consumption and withdrawal values for cellulosic biomass to ethanol are listed in Table 1. The yield from non-irrigated cellulosic grasses is assumed at 17 tonne/ha (Dominguez-Faus et al., 2009; Kiniry et al., 2005) with a 40% increased yield if irrigated (same as US corn). The irrigated cellulosic biomass embodies over 60 times more consumptive fresh water per km traveled than the non-irrigated biomass.

Table 1
Water embodied in converting irrigated and non-irrigated cellulosic rangeland grasses (e.g. switchgrass) into E85 ethanol blends for light duty vehicle travel that includes water for irrigation and ethanol processing plants.

	Crop yield (tonne/ha)	L H_20/L ethanol	Consumption (L H_20/km)	Withdrawal (L H_20/km)
Irrigated cellulosic biomass	24	490	66	66
Non-irrigated cellulosic biomass	17	7.3	1.1	1.5

As there is no current practice of harvesting rangeland grasses, the water usage characteristics for cellulosic biomass energy crop farming are assumed similar to corn.

The information presented in Fig. 1 illustrates the distribution of the percentage of km driven by LDVs on each fuel during 2005 when 15.5 GL of ethanol were produced. The vast majority of km were driven on gasoline often mixed with either methyl tert-butyl ether (MTBE) or up to 10% ethanol. For analyses such as these, it is important to pay attention to the number of km driven on any particular fuel. This information allows new perspectives on the economic (new technology), social (driving and fueling behavior), and environmental (water use and emissions) effects from using the fuel. Figs. 2 and 3 illustrates the projected percentages of km driven by LDVs in 2030 using each fuel as analyzed in the two scenarios. One important conclusion is that there are stark differences in the number of driving km that are projected using different fuels in 2030 versus 2005. Other than hydrogen fuel cell vehicles (which are only available in small production numbers at this time), all of the other fuels are commercially available to consumers. Even for electric vehicles (EV), while not yet economically attractive, a consumer can purchase an EV from Tesla Motors.

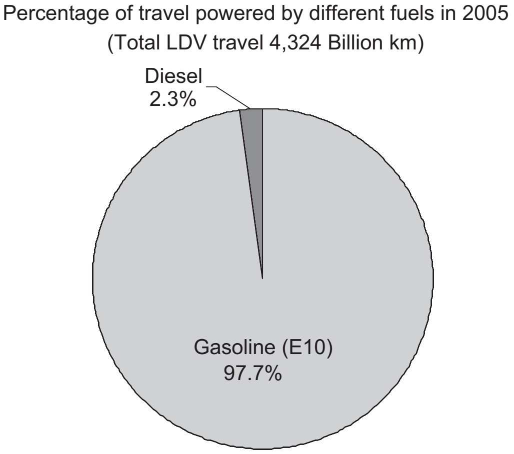

Fig. 1. The number of km driven on each fuel in LDVs in 2005.

The average water consumption and withdrawal estimates for the two analyzed scenarios (AEO and NETL, see Figs. 2 and 3 and Appendices) are plotted over time in Figs. 4 and 5, respectively. In 2005 it is estimated that 4300 and 10,300 billion liters of water were consumed and withdrawn, respectively, for LDV travel. By 2030, the projected LDV fuel water consumption could be as much as 13,700 GL/yr and water withdrawal as much as 22,700 and 27,400 GL/yr (Figs. 4 and 5) for the AEO reference and NETL cases, respectively. The total US projected water consumption does not vary significantly between the NETL and AEO case. This similarity is driven by the analysis that incorporates the ethanol usage of the RFS of EISA 2007 equally in both scenarios and the fact that most irrigation water withdrawn is consumed.

The projected water withdrawal for the NETL case is projected to be 20% higher than the AEO case in 2030, largely due to water withdrawals associated with the electricity for plug-in electric vehicles (PHEVs) and EVs. The relatively high withdrawal rates, 68 L/kWh average for 2005 US grid, for thermoelectric cooling of power generation plants dwarf those of consumption 1.2 L/kWh. However, the USGS (Hutson et al., 2004) notes that total US thermoelectric withdrawal has remained relatively flat since 1975 at 720–790 GL/d (190 GL/d saline water) even though electricity

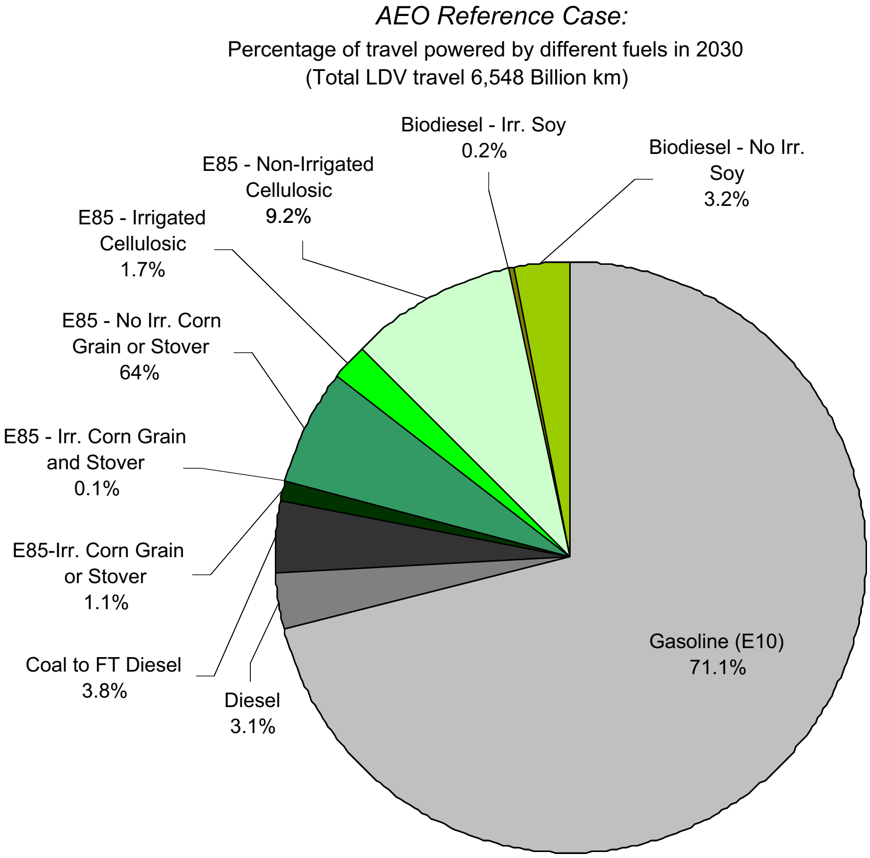

Fig. 2. The number of km driven on each fuel used in the analysis of the *AEO 2008 reference case* scenario.

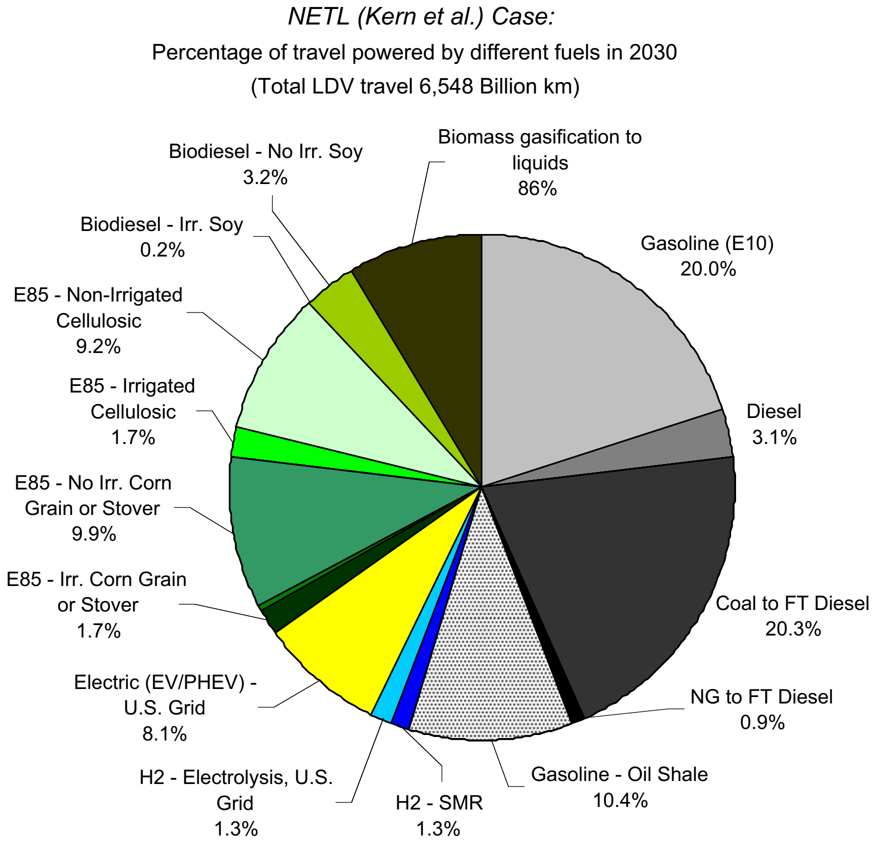

Fig. 3. The number of km driven on each fuel used in the analysis of the *NETL scenario*.

generation has steadily increased. Thus, attributing water withdrawal to transportation using electricity as a fuel *does not* explicitly mean that overall water thermoelectric withdrawal increases. Unfortunately decreasing or steady thermoelectric withdrawal rates are usually associated with increases in consumption rates (such as switching from open loop to closed-loop cooling). On the basis of the AEO 2008 electricity projections (EIA, 2008) together with NETL thermoelectric water withdrawal projections (NETL, 2008), a decreasing rate of water withdrawal for electricity generation can be projected. The 2030 withdrawal rate is projected to be 53 L/kWh assuming 5.2 trillion kWh of generation and 740 GL/d in total thermoelectric withdrawal. Using the same rationale for water consumption rates due to electricity generation, a steady rate of 1.2 L/kWh is assumed over the analysis period. In this case the total electricity generation and associated water consumption are projected to increase at the same rate while withdrawals remain level. In scenarios where carbon capture systems are employed to reduce emissions of greenhouse gases, the electric power water consumption rate is projected to increase to 2.4 L/kWh by 2030 (see Section 4.3 for discussion).

It is *very important* to note that the assumptions used in this paper regarding the amount of irrigated water used for biofuel feedstocks effectively dominate the overall estimates for total LDV embodied water withdrawal and consumption. In the examples plotted in Figs. 4 and 5, the US average value of 66 L H_2O/km (81% allocation factor) was used for water consumption and 82 L H_2O/km for withdrawal due to driving on E85 from *irrigated corn*. Considering only the 10 corn-growing states of the Midwest (Kansas, Illinois, Indiana, Iowa, Michigan, Minnesota, Nebraska, Ohio, South Dakota, and Wisconsin) approximately 15% of the corn bushels (1.25 billion out of 8.4 billion in 2003) are irrigated (USDA, 1998 and 2003; NASS, 2008). But due to high percentages of irrigated corn in Kansas (73% in 2003) and Nebraska (76% in 2003), the irrigation totals for corn grain in these 10 states are high at 9770 GL (68%) out of the 14,380 GL US total for corn seed in 2003 (USDA, 1998 and 2003). Kansas and Nebraska (which lie over the Ogallala Aquifer) alone accounted for 8930 GL of water for irrigating seed corn, and driving on irrigated corn ethanol E85 from these 10 "corn belt" states results in a similar consumption and withdrawal intensity as the US average. However, the sustainable growth of irrigated crops is determined regionally over time by aquifer recharge, rainfall, irrigation method, and soil quality. While irrigated farms in Nebraska have managed aquifer water quantity well, much area in southwest Kansas that resides over the Ogallala has a significantly decreased (over 8 m) water table compared to 50 years ago (McGuire, 2007). Future analyses should take into account these and other regional sustainability concerns.

3. Foreign oil for domestic water?

The estimated increases in US water usage for LDV travel from 2005 to 2030 are 225% for consumption and 120% (AEO) and 170% (NETL) for withdrawal. These increases far outpace the expected increase of 51% for LDV km traveled. In 2005, 77% of the 4270 GL/yr (1130 Bgal/yr) of embodied water consumption for LDV transportation was associated with ethanol. Therefore, before ethanol began replacing MTBE as an oxygenate in gasoline (driven by concerns over groundwater *quality*), water usage for transportation fuels was insignificant on a national scale.

As more agricultural products are used for transportation, the US is inherently increasing the link between water consumption, energy, and driving habits. Historically, agricultural water consumption has

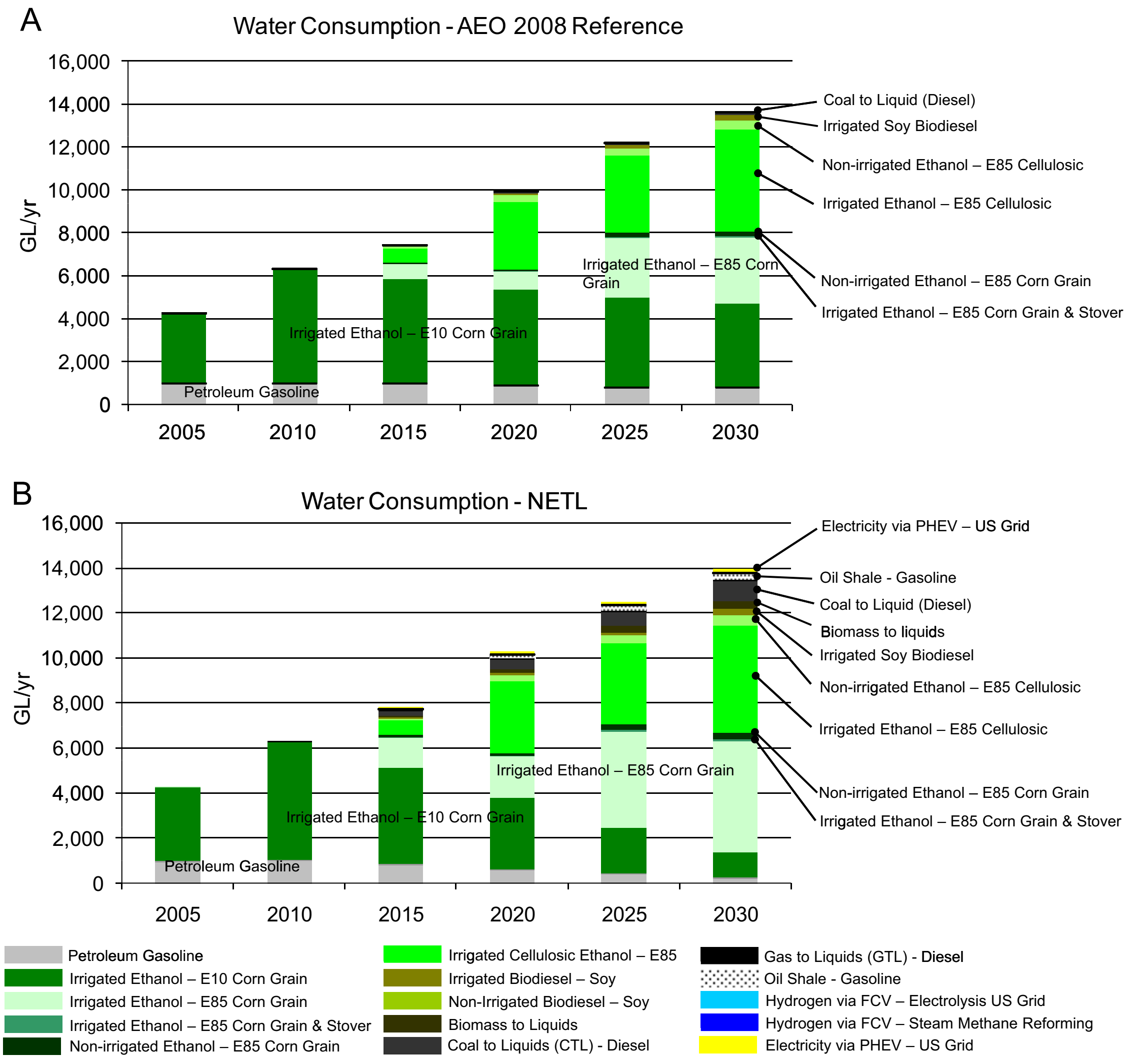

Fig. 4. The *average* water consumption (billion liters per year, GL/yr) for LDV travel for the AEO 2008 reference case (A) and NETL: Kern et al. case (B). Total US fresh water consumption in 1995 was 138,000 GL/yr.

been the result of production of food and fiber. In the future, transportation may become a significant factor in national water consumption. Additional increases in water usage for the NETL case are associated with thermoelectric power generation for LDV travel using electricity and hydrogen (via electrolysis). Water is already being withdrawn for thermoelectric purposes, but in the future significant water usage might be associated with the electrified portion of the transportation sector in addition to the residential, commercial, and industrial sectors.

A significant increase in embodied domestic water use for driving should *not* be viewed as *wholly* good or bad: the increase is something that should be considered by policy makers as part of the alternative fuels discussion should focus upon sustainable use of water resources. For the United States, the benefits of domestically sourced biofuels and electricity must be weighed against potentially negative environmental impacts. Examples of possible negative impacts for current US-based ethanol production include nitrogen/fertilizer runoff (Rabalais et al., 2007; Twomey et al., 2009), increases in overall water consumption, and regional/local depletion of aquifers. Recognition of these problems has led to a search for biofuel feedstocks (e.g. switchgrass) and other organisms that may require little to no irrigation and/or fertilizers or that can use lower quality water (e.g. algae).

National water consumption data for recent years is not available as the USGS stopped collecting water consumption data after its 1995 survey (see Table 2). In 2005, approximately 15.5 GL of corn ethanol went toward blending 62% of the nation's gasoline with up to 10% ethanol (EIA, 2008). The water consumption and withdrawal associated with this ethanol were approximately 3260 and 4290 GL, respectively. Using the 1995 ratio of consumption/withdrawal (61%) for irrigation this water consumption for ethanol is 2.9% of the total water consumed for irrigation and 2.4% of the nation's total water consumption (using the 1995 USGS baselines) (Solley et al., 1998). For comparison to another sector operating in the energy-water nexus, thermoelectric power generation accounted 3.3% of total water consumption in 1995 (Solley et al., 1998).

For 2030, the LDV transportation water consumption estimates from the AEO and NETL scenarios are approximately 10% of 1995 US fresh water consumption (see Table 2). This water consumption level holds even for the NETL case (Fig. 3) where the LDV *petroleum-traveled* km are projected to be only 20% on gasoline and 3.1% on diesel totaling 1510 billion km. For the NETL case the water consumption for other gasoline and diesel feedstocks are accounted for with oil shale contributing to gasoline for 680 billion km (10.4%) and coal-to-liquids (CTL),

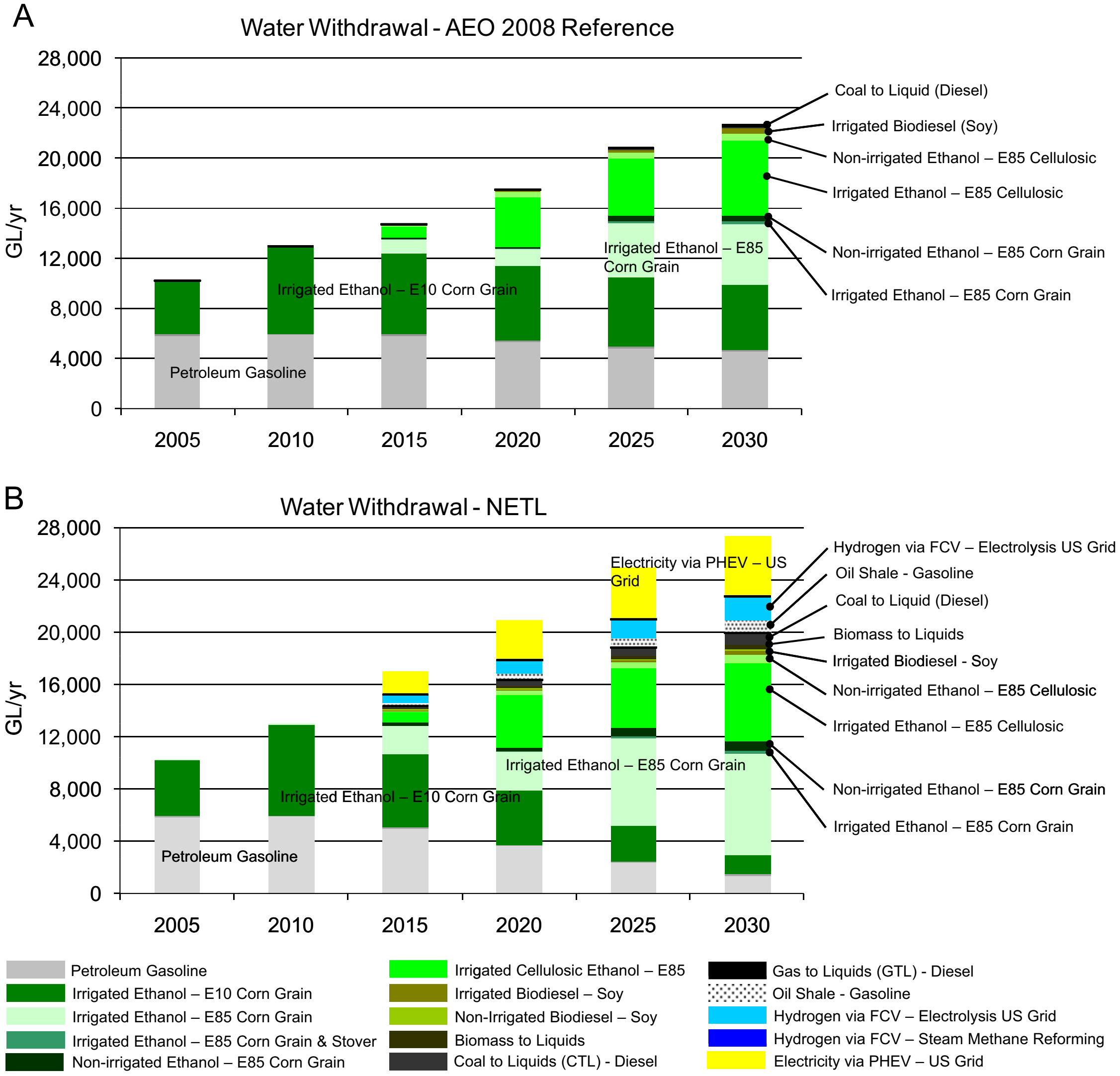

Fig. 5. The *average* water withdrawal (billion liters per year, GL) for LDV travel for the AEO 2008 reference case (A) and NETL: Kern et al. case (B). Total US fresh water withdrawal in 2000 was 477,000 GL/yr.

Table 2
Water consumption embodied in the fuels for light duty vehicles is projected to steadily increase, primarily due to agriculture for biofuel feedstocks.

	1995	2005	2010	2015	2020	2025	2030
US fresh water consumption (GL/yr)	138,200	–	–	–	–	–	–
US water consumption forIrrigation (GL/yr)	113,560	–	–	–	–	–	–
Estimated water consumption for LDV travel (GL/yr)	–	4,300	6300	7500	9900	12,200	13,700
Water consumption for LDV travel as a % of 1995 total US water consumption (%)	–	3.1	4.6	5.4	7.2	8.9	9.9
Water consumption for biofuels in LDV travel as a % of 1995 total US water consumption (%)	–	2.4	3.9	4.6	6.5	8.2	9.2
% of water consumption for LDV travel due to biofuels (%)	–	77	84	86	90	92	93

The percentages of water consumption are based upon 1995 data (Solley et al., 1998).

gas-to-liquids (GTL), and soy contributing to diesel for 1610 billion km (25%).

A reasonable question is to what extent this water usage is in addition to the water usage that would have occurred anyway without the production of alternative fuels. Electric power for electric vehicles will be all incremental additions to water consumption even if the majority of electricity consumption is limited to off-peak demand hours. There is anecdotal evidence that in the last few years excess corn production and stocks have been used up by ethanol production and that previously fallow land is now being used for growing corn. In 2004 and 2005, corn stock levels were 18% of annual corn production whereas in 2006–2008, US corn stock levels were approximately 12% of annual production (USDA, 2009). Furthermore, US crop land for corn was between 30.6 and 33.1 million hectares (Mha) from 2000 to 2006, but then increased to 37.8 Mha in 2007 and 34.8 Mha in 2008 (NASS, 2008). This shows that more land was used for corn production in 2007–2008, and a recent study shows that the incremental corn production is occurring in higher irrigation intensive areas (Chiu et al., 2009). In other words, additional biofuels production seems to already be resulting in incremental water withdrawal and consumption and likely to do so in the future.

4. Discussion

4.1. Comments on assumptions and range of projections

It is important to understand that the results presented in this paper can vary widely if different (but still plausible) assumptions are made in projecting future water usage related to transportation fuels. A major source of uncertainty in these projections is the assumption of which technologies and processes will be used to produce and use the fuel. For example, consider converting coal or biomass into fuel via a gasification process. Whether all of the hydrocarbon content in the coal to be converted to diesel fuel, converted into gasoline, propane, or some other fuel affects the water impact. Each refining process may consume and withdraw a similar order of magnitude of water, but various other species of constituent gases can be part of producing solid hydrocarbons or carbohydrates to a specific fuel. In turn, each LDV that uses the fuel will consume it at a different efficiency. Simply considering the same vehicle with a gasoline versus diesel engine and their different fuel efficiencies brings this point to life. Therefore, the assumption in this paper that all coal to liquids is used to synthesize diesel fuel is clearly a generalization of future reality. It could just as easily have been assumed that half of the coal would be converted to methane as a substitute for natural gas-to-liquids processes or to gasoline. Making these changes in our analysis might affect the projected water impacts, however the general conclusions would likely be unchanged.

Additionally, aside from the embedded AEO LDV fuel efficiency increases, the analysis in this paper did not assume any technological, social, or design changes that could significantly decrease water usage for biofuels and electricity generation. Such changes could include increased use of drip irrigation, dry cooling systems for thermoelectric power plants, and decarbonization of fuels (the potential impact of carbon dioxide capture systems on increasing water consumption in power plant is discussed below in Section 4.3). Further increases in LDV fuel efficiency, barring large increases in km driven, should also decrease both the amount of fuel and water consumed.

4.2. Regional and local effects

While the overall US water intensity of transportation fuels is important in considering the scope of the water-fuel issue, it is the regional and local impacts on water usage that will dictate where and how fuels are made. Prior to 2005 (and the widespread replacement of MTBE by ethanol in gasoline), the petroleum refining process accounted for the vast majority of water use for LDV fuels. Petroleum refineries consume relatively little water per liter of final product as these usage amounted to only 1000 GL/yr consumption and 5800 GL/yr withdrawal nationally in 2005. Since approximately half of the US refineries are located on coastal areas (to refine imports), refiners can often use seawater for cooling, resulting in even lower impact on fresh water resources. Most future alternatives to petroleum-based fuels are more water intensive and will be mined, farmed, and refined in the interior of the country where water supplies are typically more limited. Such regional shifts in water usage triggered by transition from gasoline to biofuels can have unforeseen consequences.

Fuels made from biomass, irrigated or not, are likely to be centered heavily in the Midwest and Eastern US where good soil and abundant rainfall exists compared to the US to the West of the Great Plains (Milbrandt, 2005). However as noted by Chiu et al. (2009), ethanol production is leading to relatively large rates of water consumption in states such as New Mexico, Colorado, and California, Western states that have increasing water stress or are currently undergoing drought conditions. Additionally, the water needed for 'at scale' ethanol and biodiesel refineries can put a localized strain on water resources, preventing some locales from allowing ethanol plants, even though a larger region may theoretically handle the water load (Keeny and Muller, 2006).

The water intensity for mining and refining fuels made from oil shale will be concentrated near the resource that exists around the interstate boundaries of Wyoming, Colorado, and Utah. Surface water from this area feeds into the Green River and eventually the Colorado River—an already stressed water resource whose users from Utah to Southern California may need to readjust water habits (Scripps, 2008). Converting coal resources to liquid diesel or other fuels could potentially be done near the mine, as pipelines are efficient for transporting mass quantities of liquids, or far from the mine as rail infrastructure already exists to ship coal for power generation. On the other hand, if coal to liquids conversion begins on a large scale, new pipeline and/or additional rail infrastructure will likely be needed.

For some fuels, such as electricity for PHEV/EVs or hydrogen produced via electrolysis, the water demand will be felt relatively uniformly across the US depending mostly upon the power generation mix of the grid near the user. No matter what fuel is produced, some regions will be more amenable from a water resource standpoint than others, and it is important that water resources be considered when planning for the mining, farming, processing, and refining of new alternative fuels. Even non-irrigated biofuel crops are using water resources from watersheds that could otherwise be used for growing food or recharging aquifers. Any large scale production of biofuel crops will have a measurable effect on the balance of the regional water cycle with the commensurate possibility of unintended consequences. Whether groundwater or surface water is needed, proper accounting for input flows, rainfall, and aquifer recharge will be needed to ensure for sustainable use of water. This accounting will need to be done by coordinating within and among watersheds to account for the water cycle that knows no political boundaries. Future work should focus upon these concerns about regional water cycles and sustainability.

4.3. Impact of carbon dioxide capture at fossil fuel power plants

In looking to a future carbon-constrained world, fossil fueled power plants may need to scrub carbon dioxide from pre or post-combustion gases. Adding carbon dioxide capture systems onto fossil power plants will significantly increase water consumption per net electricity generated from the power plants unless dry cooling is also implemented. The primary reason is that a significant portion of power plant fuel is required to power the CO_2 capture process and compress the CO_2 for transport and injection into a sequestration site.

Here we consider the water impacts of CO_2 capture by using average projections by the National Energy Technology Laboratory (NETL, 2008). For the NETL *fuel projection* case by Kern et al. shown in Fig. 3, the water consumption associated with charging PHEVs jumped from 240 to between 260 and 380 GL/yr in 2030. This increased water consumption for PHEVs uses the projection that when incorporating CO_2 capture scenarios thermoelectric water consumption will be 20–95% higher in 2030: 22–35 GL/day *with* CO_2*capture* versus 18 GL/day *without* CO_2*capture*. Dry cooling systems were considered as part of the scenarios run by the DOE in projecting water needs for power generation (NETL, 2008). The water withdrawal associated with electric vehicle travel, charged using electricity from power plants with or without CO_2 capture, is not expected to increase appreciably as new and existing power plants are not expected to use any new open-loop cooling systems. Most scenarios actually project slight decline in withdrawals for thermoelectric power (NETL, 2008). The additional future water usage due to increased cooling load from CO_2 capture at power plants should be manageable. Increased usage of electricity for LDV travel in PHEV/EVs could however have locally significant negative impact upon availability of water resources even though Fig. 5 shows a small overall contribution to water consumption in the US.

4.4. Comparisons with other studies of water for transportation

A few studies from other authors have also investigated the water needs for fuels, mostly concerned with biofuels. Already referenced, Chiu et al. (2009) examined the state-wide differences in irrigation water embedded in bioethanol from corn in the United States. They estimated that the irrigation intensity in states producing corn ethanol ranged from 5 to 2138 L H_2O/L ethanol, thus emphasizing regional differences can be vast. Generally states west of the Mississippi River require large quantities of irrigation for corn agriculture versus those in the east.

The work of Wu et al. (2009) is most similar to our analysis presented in this and past work, but with an extended analysis of water requirements for oil production in Saudi Arabia (Wu et al., 2009; King and Webber, 2008a; King and Webber, 2008b). The final values of 2–7 L H_2O/L gasoline from conventional petroleum and tar sands are in agreement between Wu et al. (2009) and the present work based upon King and Webber (2008b). While Wu et al. (2009) assume that no irrigation will be used for switchgrass cultivated for biofuel feedstock, we project future water for transportation fuels by assuming that 17% of cellulosic biomass will be irrigated—the same amount for corn. However, we both use information from the USGS that 20–30% of withdrawn irrigation water is lost or returned to source, and is thus not counted as consumption. Chui et al. (2009) do not account for this difference and assume all withdrawn irrigation water is consumed, making their values for direct water consumption for corn ethanol higher than most other estimates. The available data on irrigation consumption and withdrawal from both the USDA and USGS is difficult to correlate, leading to difficulty in presenting a common analysis. Some of this difficulty arises from the variations in irrigation water supply, irrigation methods, and local climates, and the USGS Water Use Survey estimates this information on a state level.

Gerbens-Leenes et al. (2009a) use their well-established water footprint methodology to compare the total blue water (surface water and groundwater) and green water (precipitation) evapotranspirated for different crops that can be converted to liquid fuels or combusted for electricity (Gerbens-Leenes et al., 2009a). Thus, because the work reports total water requirements for biofuel feedstocks by including evapotranspiration, the work is aimed more broadly for global water resources management. Their broad global level analysis compares footprints (m^3 of water per gigajoule of liquid biofuel) where for each feedstock crop the minimum and maximum footprint values generally vary by an order of magnitude, and for wheat and sorghum 2 orders of magnitude. For example, ethanol from maize ranges from 40 to 380 m^3 H_2O/GJ, equivalent to 940–8900 L H_2O/L ethanol. While Pfister and Hellweg correctly argue that regional water availability knowledge is required for water resource management to make use of water footprints from bioenergy and other water uses, Gerbenes-Leenes et al. argue Pfister and Hellweg's suggested method is arbitrary and thus uninformative (Pfister and Hellweg, 2009; Gerbens-Leenes et al., 2009b) .

Although other water-transportation nexus studies have examined a number of fuels from the perspective of the volume of water required per volume of liquid fuel, they have not related the water consumption and withdrawal to actual vehicle travel as in this manuscript. Furthermore, we provide a first order analysis of how the use of water for transportation fuels may develop. Thus, the present work provides a starting point for future studies to perform regional water resource assessments aimed at estimating how water availability may change in the future as result of the scenarios for alternative fuels development outlined in this paper. Future comprehensive water usage assessments could include factors such as variation of rates of evapotranspiration and aquifer recharge.

5. Conclusions

Since the mandated phase-out of MTBE and subsequent ethanol blend into gasoline, the water consumed by the US LDV transportation sector has increased from less than 1% to approximately 2.4% of the nation's water consumption. This increase is primarily due to the farming of corn as an energy crop. It is likely that the majority of the water usage for ethanol production to date would have happened anyway (as excess corn production intended for food was being utilized). Although the future for water consumption for transportation fuels is not clear, this paper has pointed to several areas of concern. Utilization of agricultural land for biofuels is expanding and future growth will increasingly come from utilizing previously fallow land. As this happens the impact on local water availability and regional impacts on the water cycle will grow. The analysis presented in this paper shows a considerable increase in water consumption and withdrawal for both future fuel scenarios used in this study that vary significantly from today's fuel mix. Increasing fuel usage, along with a transition to more biofuels will drive future increases in the withdrawal and consumption of water. The amount of this increase depends heavily upon which alternative fuels the US will produce The US has considerable ability to minimize the water impacts by considering embodied water consumption as a factor in future energy planning.

By 2030 it is estimated (for two fuel projections analyzed in this paper) that, farming, mining, and refining of LDV fuels will consume approximately 14,000 billion liters of water per year, 10% of estimated US fresh water consumption. Water withdrawal for LDVs in 2030 is projected to be 22,700–27,400 GL/yr. Agricultural irrigation for biofuel feedstock heavily dominates water usage for LDV travel accounting for 80–85% and 45–65% of the 2030 total consumption and withdrawal, respectively.

When directly viewing the AEO and NETL fuel scenarios (Table A1 and Figs. 2 and 3) used as basis for this study, one can see apparent discrepancies between the mix and proportions of *fuels* and *km* associated with LDVs. This difference is primarily due to understanding fuel consumption in terms of km driven when accounting for LDV technologies. The results of this paper emphasize that understanding the full life cycle of transportation is important, not simply the fuel. Maximizing km traveled per amount of water and energy should be attempted when possible.

It is more important for the driver to be able to travel to where and when desired than it is for the driver to know how many equivalent barrels of oil are being used. Focusing on the true customer needs of LDV owners – a certain *distance* to be traveled or *task* to be performed – versus fuel and energy consumption will lead us to make better long term decisions about infrastructure and technology adoptions that are more energy efficient and environmentally benign.

In producing a certain amount of biomass for fuels it is necessary to weigh the tradeoffs between more acreage for lesser irrigated crops, at lower yield and with more tractor fuel, versus less acreage and higher irrigation. Although using irrigated crops to produce biofuels shifts a significant portion of embodied water into the transportation sector, this does not lead to a conclusion the US should abandon biofuels or limit future production. However the possibility of negative impacts on the water cycle both regionally and locally should be carefully considered before implementing incentives or other policy levers that will impact fuel production patterns. Such policies can create unexpected scenarios, such as the exporting of biofuels from regions with water deficits to regions with ample water, possibly creating negative economic and environmental impacts. Similarly, higher water withdrawal for PHEVs and hydrogen-powered vehicles does not mean that the US should abandon adopting policies that promote their use.

Water resources in many areas are effectively finite resources and in some cases are not renewable except on geologic time scales. The US should look for ways to sustainably manage domestic water resources by trade of both energy and other products. By understanding the entire fuel system from mining and farming to consumer use, the US can transition its fuel production, water use, trade, and driving patterns to a more renewable and sustainable future.

Appendix A. Analysis background and assumptions

A.1. Fuel and driving scenarios

In addition to the Annual Energy Outlook 2008 EIA scenario for future usage of transportation fuels (EIA, 2008), the predictions of Kern et al. of NETL provide an aggressive move toward what the authors call an ‘advantageous interdependence’ scenario for converting to fuels based upon domestic and renewable supplies (Kern et al., 2007). The NETL scenario is based upon the mileage (km driven) from the AEO 2007 High Price case scenario, with an emphasis on reducing reliance on imported petroleum.

Each analysis case assumes the same number of km driven for LDVs each year, with both using 4324 billion km in 2005 as the starting point and 6548 billion km in 2030. It is important to note that the final water usage and analyzed driving distance scenarios are *not* direct representations of the situations from the AEO and NETL. Both the AEO and NETL scenarios describe different fuel mixes using units of energy, not km, for the consumption in the transportation sector (see Table A1). LDVs only consume a portion (58%, see Appendix A.3) of energy in the transportation sector. Because this analysis uses *kilometers driven* as a basis for calculating water consumption and withdrawal, we must convert energy into km for each fuel. This approach inherently necessitates making some additional assumptions, but they have been restricted to follow the spirit of the scenarios (see Appendix A.3).

The calculations and methodology for estimating the water consumption and withdrawal rate, in liters of water per kilometer traveled (L H_2O/km), for most of the transportation fuels studied here is presented in previous work (King and Webber, 2008a; King and Webber, 2008b).

A.2. Incorporation of renewable fuels standard (EISA, 2007)

The 2008 AEO scenario has now incorporated the effects from the RFS signed into law as part of EISA in 2007 (EISA, 2007). The RFS mandates that sales of biofuels increases to 136 GL/yr (gigaliters per year) by 2022, and ethanol from corn grain is effectively limited to 57 GL/yr (EISA, 2007). This corn ethanol limitation necessitates future incorporation of cellulosic-based ethanol, or perhaps increased imports from countries such as Brazil regardless of whether legislators change tariff laws. Therefore, for ethanol mandated beyond the 57 GL/yr limit for corn grain ethanol, it is assumed all biomass is grown within the US and that the agricultural water consumption and withdrawal characteristics follow values for ethanol from general cellulosic biomass (DOE, 2009; Kiniry et al., 2005).

Table A1
Scenarios representing consumption of liquid fuels (Table 2 of AEO) for all sectors that are used in 2030 as a basis for the water analysis of this manuscript (MMBBl/d of oil equivalent) (EIA, 2008; Kern et al., 2007).

Fuel	AEO Ref.	NETL
Petroleum	20.4	15.2
CTL	0.3	2.4
Natural gas to liquids	0.0	0.1
Oil shale	0.0	1.7
Tar sands	0.0	0.45
Ethanol (corn)	0.2	0.54
Ethanol (cellulosic)	0.4	0.46
Methane hydrates	0.0	1.0
Electricity-PHEV	0.0	1.05
Biomass to liquids	0.0	1.0
Hydrogen -FCV	0.0	0.22
Vehicle fuel efficiency	0.0	0.94[a]

[a] Ignored for this analysis is the efficiency improvement in AEO 2008 in comparison to the AEO 2007 as Kern et al. (2007) used the AEO 2007.

Table A2 shows the amount of ethanol and biodiesel assumed for the present analysis. The table values are governed by the RFS up until 2022 with assumed increases in production (7.6 GL/yr) for years past 2022 in order to match the time frame of the AEO cases that project until 2030. These increases correspond to 159 and 197 GL of biofuels for 2025 and 2030, respectively. Quantities of biodiesel are only stipulated until 2012 when 3.8 GL is to be consumed. We assume significant increases in biodiesel through 2030.

A.3. Calculating km driven per fuel in LDVs

In using the fuel projection scenarios analyzed, the amount of fuel, usually in British thermal units (Btus) and/or equivalent barrels (BBls) of oil is presented, rather than the number of km driven using a particular fuel (see Table A1). In this paper, the number of km driven are calculated and then multiplied by the appropriate fuel system water consumption and withdrawal rate in units of L H_2O/km. This approach focuses on the capability of existing technologies to convert fuels into the desired output, rather than simply the energy content of fuels. That is to say, a person driving a car does not have a target number of liters that he would like to use in a day, but he does have a target distance he would like to travel.

Gasoline is used as the ‘catch all’ fuel in that all projected targets for using fuels other than petroleum gasoline, or E10, are fulfilled such that all km not otherwise accounted for are assumed driven by E10 gasohol/gasoline. This assures that the exact target for total number of km driven by LDVs is met.

Unfortunately, the AEO scenario only specifies ethanol consumed as E85 and not that blended into gasoline, or E10, as an oxygenate. The ethanol put into E10 gasoline, or gasohol, is incorporated by assuming that all ethanol is used to make E10 until it composes 10% of the volume of projected gasoline usage. After that, it is assumed that any additional ethanol goes into E85. This assumption is not too restrictive as only 201 million

Table A2
Fuel quantities assumed for 2005 and RFS mandate through 2022 in GL/yr (Bgal/yr in parentheses as indicated by RFS) (EIA, 2008; EISA, 2007).

	2005	2010	2015	2022	2025	2030
Corn Grain Ethanol	15.5 (4.1)	43.1 (11.4)	56.8 (15)	56.8 (15)	56.8 (15)	56.8 (15)
Cellulosic Ethanol	0 (0)	0.1 (0.4)	3.0 (11.4)	60.6 (16)	**60.6 (16)**	**60.6 (16)**
Biodiesel	0.1 (0.4)	2.5 (.65)	**3.8 (1)**	**9.5 (2.5)**	**11.4 (3)**	**22.7 (6)**
"Other" Advanced biofuels	0 (0)	3.2 (0.85)	5.7 (1.5)	**9.5 (2.5)**	**30.3 (8)**	**37.9 (10)**
Total	15.9 (4.2)	49.2 (13.0)	77.6 (20.5)	136 (36)	*159 (42)*	*197 (52)*

The authors estimated further increases (in italics and bold) for (a) 2022–2030 to match with AEO time projection time frames and (b) for biodiesel after year 2012 when 3.8 GL/yr (1 Bgal/yr) for biodiesel is stipulated. Bold values in the table represent author assumptions for projected consumption. Bold and underlined values in the table represent legislative mandates.

Table A3
For the analysis, the LDV fleet in the US is assumed to follow the following gasoline fuel efficiencies, km/L (miles per gallon) and annual km (miles) driven over the next 22 years (EIA, 2008).

	2005	2010	2015	2020	2025	2030
AEO Ref and NETL, km/L (mpg)	46.8 (19.9)	47.7 (20.3)	50.6 (21.5)	55.7 (23.7)	61.4 (26.1)	65.6 (27.9)
Billions of kilometers (Miles)	4324 (2687)	4469 (2777)	4921 (3058)	5432 (3375)	5982 (3717)	6548 (4069)

liters of E85 were consumed in 2005 compared to over 15 billion liters of total ethanol produced in the US (EIA, 2008). Thus, the 2005 ethanol volume used in E85 was only about 1% of the total. In the future, it is certainly possible that other proportions of ethanol can be blended into gasoline, possibly causing many different vehicle fuel efficiencies. This scenario is not considered.

To estimate the number of LDV km driven on each fuel, the percentage of fuel consumption used for LDVs must be known. The Transportation Energy Databook (Davis and Diegel, 2006) provides some insight for these assumptions showing that in 2003 LDVs consumed 91.6% of the gasoline and 4.9% of the diesel in the US. Additionally, in 2005 the US consumed 28 out of 100 total quads of energy in the transportation sector (EIA, 2008). Out of the energy consumed for transportation, 56–60% is used for LDV travel amounting to 17.1 exajoules or 8.5 MMBBl/d of oil equivalent (EIA, 2008). Thus, 58% is used as the ratio of a transportation fuel that will be used for LDVs versus for other purposes (heavy trucks, air, rail, etc.). Specifically this analysis assumes the following percentages of consumption in the class LDVs for the alternative and unconventional fossil fuels: ethanol—100%; electricity/hydrogen—100%; biodiesel/CTL/gas-to-liquids (GTL)/oil shale to gasoline/tar sands to gasoline—58%, and compressed natural gas (CNG)—0%.

For 2030, the NETL case explicitly targets two fuel sources not explicitly incorporated in the AEO cases: methane hydrates (1 MMBBl/d oil equivalent) and biomass gasification to liquids (1 MMBBl/d oil equivalent). At the time of this writing, no data are available on the water withdrawal and consumption for producing fuel from methane hydrates. Consequently hydrates are not included in our analysis of the NETL scenario. Because the methane hydrate resources lies in the ocean floors, it is likely that little to no direct fresh water resources would be used in the mining of methane hydrates.

The refining water consumption and withdrawal rates for biomass gasification to liquids are assumed the same as for coal to liquids. Since new coal gasification facilities will likely be designed for biomass blending, our assumption for water usage rates is within reason (Boardman, 2007). No water use for irrigation of biomass for gasification is assumed because of the unknown and varied types of materials that could be used in the future (wood chips, trash, etc.). It is recognized that some biomass used for gasification can very likely come from irrigated crops such that our estimate will be a lower bound.

The NETL case that was analyzed includes an additional 0.94 MMBBl/d of oil equivalent savings attributed to fuel efficiency over and above the AEO 2007 high price case (see Table A1) (Kern et al., 2007). This efficiency increase was assumed before the signing of the Energy Independence and Security Act (EISA) of 2007, which raised the Corporate Average Fuel Economy (CAFE) standards more than the NETL case had assumed. Thus, the increased efficiency gain for petroleum reduction is ignored for the NETL scenario. The projected increasing fuel efficiencies (see Table A3) for gasoline LDVs are accounted for proportionally from the starting value in 2005. For the non-petroleum fuels (for example, electricity), LDV efficiencies are assumed to change at the same rate as for gasoline shown in Table A3. For example, from 2005 to 2030 the EIA reference case shows a 40% increase in fuel efficiency for gasoline equivalent liters. Applying this increase to electrically driven km gives an increase from 3.5 km/kWh(King and Webber, 2008a) in 2005 to 5.0 km/kWh in 2030.

For incorporating hydrogen, NETL assumes that by 2030, 8 million fuel cell vehicles (FCV) will displace 0.22 MMBBl/d of oil by obtaining hydrogen via coal gasification. It is assumed that these FCVs drive an average 56 km per day, or 164 billion km in 2030, on hydrogen evenly split between steam methane reforming (SMR) and electrolysis from the US grid.

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