The Water Intensity of the Plugged-In Automotive Economy

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Received July 02, 2007. Revised manuscript received January 07, 2008. Accepted January 08, 2008.

Converting light-duty vehicles from full gasoline power to electric power, by using either hybrid electric vehicles or fully electric power vehicles, is likely to increase demand for water resources. In the United States in 2005, drivers of 234 million cars, light trucks, and SUVs drove approximately 2.7 trillion miles and consumed over 380 million gallons of gasoline per day. We compare figures from literature and government surveys to calculate the water usage, consumption, and withdrawal, in the United States during petroleum refining and electricity generation. In displacing gasoline miles with electric miles, approximately 3 times more water is consumed (0.32 versus 0.07–0.14 gallons/mile) and over 17 times more water is withdrawn (10.6 versus 0.6 gallons/mile) primarily due to increased water cooling of thermoelectric power plants to accommodate increased electricity generation. Overall, we conclude that the impact on water resources from a widespread shift to grid-based transportation would be substantial enough to warrant consideration for relevant public policy decision-making. That is not to say that the negative impacts on water resources make such a shift undesirable, but rather this increase in water usage presents a significant potential impact on regional water resources and should be considered when planning for a plugged-in automotive economy.

1. Introduction

The shift from transportation that is powered by petroleum-based liquid fuels to those based upon other energy sources and storage materials is just beginning. Many analytical studies and policy priorities have considered transitioning to a transportation system of passenger cars and light-duty trucks that are propelled by electric motors. Typically the electricity for these motors is generated elsewhere and stored onboard (for example through batteries) or generated onboard with hydrogen fuel cells. While the benefits and drawbacks of hydrogen-powered vehicles have been extensively considered, and the hydrogen economy is a public policy priority of the Bush Administration (*1–8*), this paper will focus primarily on those vehicles that are "plugged-in" at some point in the normal cycle of their use, either as purely electric vehicles (EVs) or plug-in hybrid electric vehicles (PHEVs). PHEVs operate in electric mode for a limited distance until the stored electric energy is depleted and afterward operate using an onboard internal combustion engine for long distance trips. The PHEV is being promoted by many cities and utilities including the municipal utility of Austin, Texas, Austin Energy, via a promotional campaign called Plug-In Partners (*9, 10*).

One important consideration for both the hydrogen (*11*) and plugged-in economies that is often neglected by policy makers is the impact on water resources that a transition from a petroleum-based transportation sector would impart. Freshwater resources are critical to society and its energy usage, and they are already in duress in many parts of the United States and the world (*12–14*). Understanding the potential for public policy decisions to unexpectedly worsen the situation is valuable to know ahead of time.

For example, shifting the transportation system away from conventional petroleum-based liquid fuels to alternative sources could positively benefit one policy priority (e.g., air quality, trade balances, etc.), while worsening the impact on domestic freshwater resources. This manuscript conducts an analysis to understand how the shift from conventional petroleum based gasoline to grid-charged electric vehicles will impact the quantity of water resources used. We do not directly address *if* a shift to PHEVs or EVs is desirable, but we hope that this analysis will add information to that policy question.

In comparing the difference in water usage for the electron-based and petroleum-based automotive economies, we disregard the transport of the fuel materials for the production of the liquid fuels for traditional combustion engines in cars and for power plants that generate electricity. Furthermore, the water resources that are required for manufacturing the automobiles and power plants are not considered. The focus of this paper is on the water withdrawn and consumed in the fossil fuel extraction, petroleum refining, and electric generation processes. The basis for our electricity calculations are modern concepts of PHEVs, although EVs could be substituted interchangeably.

The approach taken in this paper is to compare the water usage, withdrawal, and consumption, on a per-mile basis relating to how cars are actually driven. For information regarding total fuel energy usage comparisons between conventional gasoline vehicles and PHEVs, see the Electric Power Research Institute 2002 report cited in the references (*15*).

2. Experimental Procedures

2.1. Driving Habits of Americans. In 2003, 136 million cars and 87 million light trucks consumed gasoline at a rate of 74.6 billion gallons per year (55.6%) and 56.3 billion gallons per year (42.0%), respectively, out of 134 billion gallons per year (Bgal/yr) used for transportation purposes (*16, 17*). Today there are approximately 234 million gasoline vehicles in the United States, and in 2005 total gasoline consumption used for transportation was 137 Bgal/yr (*17, 18*). Using annual gas consumption and miles driven, the average miles per gallon (mpg) rating for the 2003 U.S. light-duty vehicle (LDV) automotive fleet was 22.3 mpg for cars and 17.7 mpg for light trucks and sport utility vehicles (SUVs) (*16*).

We neglect the consumption of diesel because diesel contributes only 2% of the energy consumed as motor fuels for LDVs, which are the focus of this paper (90% of diesel is used for medium- and heavy-duty vehicles within the transportation sector) (*16*).

2.2. Miles Driven by Cars and Light Trucks/SUVs. In calculating the water usage for PHEVs we need to calculate

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10.1021/es0716195 CCC: $40.75
Published on Web 02/20/2008

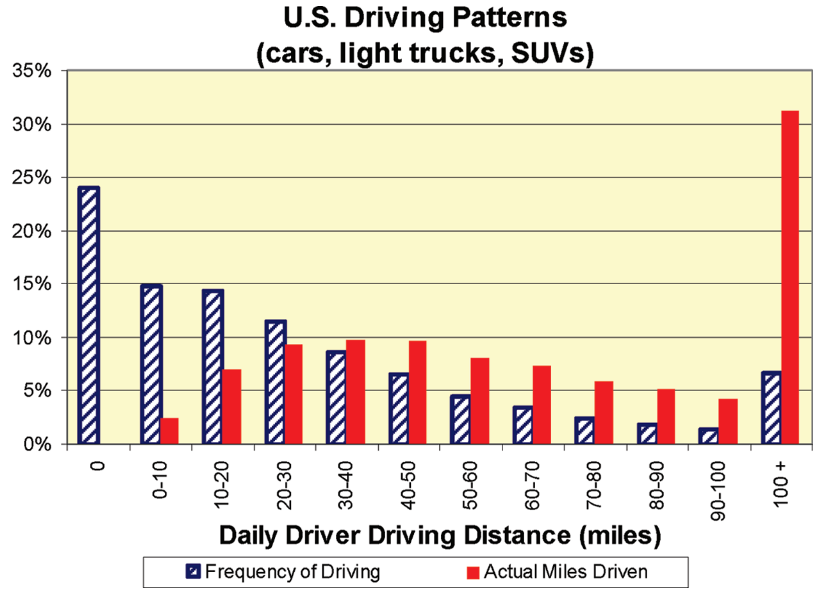

FIGURE 1. Frequency distribution of American drivers' habits shows that approximately 50% of daily drivers travel less than 40 miles, and 24% of drivers do not drive at all on any given day (*19*). Even though only 7% of drivers driver more than 100 miles/day, they account for over 30% of the miles driven per day.

the number of miles driven that are currently fueled by gasoline. Later we use this mileage basis for calculating the amount of water used for vehicles powered by gasoline using internal combustion engines (ICEs) and electricity using motors in PHEVs. In 2003 American drivers of cars and light trucks/SUVs traveled approximately 1.66 and 1.00 trillion miles, respectively, giving a total of 2.66 trillion miles for this category (*16*). Data for total miles traveled are not available more recently than 2003, but by using 2005 data for petroleum consumption and fuel economy averages for 2003 we can estimate the total miles driven for 2005. Cars used 4.6 million barrels per day (MBBl/d) and light trucks used 4.3 MBBl/d of petroleum in the form of motor fuels in 2005 (*16*). Using the mpg ratings stated earlier and assuming they stay level for 2005, this consumption corresponds to 1.57 and 1.17 trillion miles driven by cars and light trucks/SUVs, respectively, for an 80 billion mile increase from 2003 to 2005. Of the total number of miles driven by LDVs, cars were responsible for between 57% and 63% and light trucks/SUVs were responsible for 38%–43%. In going forward with calculations for ICE vehicles and PHEVs, we assume that for the miles driven in the LDV sector, cars account for 60% of the miles and light trucks/SUVs account for 40%.

The expectation that PHEVs can make a substantial impact on the LDV market is primarily because their limited electric range fits within a great preponderance of commute-oriented consumer driving patterns. Figure 1 illustrates the relative frequency of daily driving distances for American drivers (diagonal hashed bars) and the percentage of absolute miles driven by drivers within each distance category (*19*). An average value of 140–165 miles per day (30%–34% of actual driven miles) was used for the "100+" mile category to equate the 2.3 trillion miles driven an average of 68.69 miles/day for drivers driving over 30 miles (*19*).

Prior studies and statistics similarly note the prevalence of short-range driving habits for most Americans (*19–22*). The 2001 National Household Transportation Survey (NHTS) states that the average daily vehicle miles traveled per driver are 34.4 and 28.7 miles for weekdays and weekends, respectively (*19*). A 2005 DOE report discussing driving profiles of St. Louis residents shows that most vehicles travel less than 30 miles a day, and the replacement of ICE vehicles with PHEVs could result in a 75% reduction in gasoline consumption (*21*). Also, the Electric Power Research Institute states that half of the cars in the United States are driven less than 25 miles per day; consequently a PHEV with a 20-mile electric range reduces its petroleum consumption by 60% (*22*).

2.3. Plug-In Hybrid Electric Vehicle (PHEV) Background. Because the infrastructure for electricity generation and distribution is already in place, it presents an appealing opportunity for use in the transportation sector (*23, 4*) and is one factor motivating interest in the plugged-in, or electron, automotive economy. Also, the consumer products industry has improved the energy density, lifetime, and weight of battery technologies such that they can meet the demands for mass usage in electric vehicles (*24, 4*) for limited range. Thus, attention has turned toward PHEVs as a way to decrease petroleum consumption.

PHEVs can use the existing electric grid infrastructure to recharge onboard storage devices such as batteries and ultracapacitors. The bulk of this charging is expected to occur at night for typical commute-oriented driving patterns. Thus, electricity consumption by PHEVs would coincide with the diurnal decline in electricity usage in the grid making use of the electricity infrastructure at times it is less utilized (*23, 22*). Kintner-Meyer et al. calculate that 73% of U.S. travel using LDVs could be supported to drive 33 electric miles per day on the existing grid infrastructure and generation sources (*23*). They calculate that accommodating this travel with electricity via PHEVs or EVs could displace 6.5 MBBl/d, and that little to no new electric infrastructure or capacity additions are needed to enable a considerable decrease in both petroleum consumption and imports, at 31% and 52%, respectively (*17*).

In determining the specific energy (kWh/mile) required for PHEV electric travel, we use the same data as Kintner-Meyer et al. derived from the EPRI PHEV study group: compact sedans use 0.26 kWh/mile, midsize sedans use 0.30 kWh/mile, midsize SUVs use 0.38 kWh/mile, and full-size SUVs use 0.46 kWh/mile (*15, 23*). We assume that light trucks and SUVs require the same specific energy when converted as PHEVs, and large sedans are counted in the midsize category. We also assume that the ratio of (1) compact to midsize sedans and (2) midsize to full-size trucks, SUVs, and vans is one-to-one (e.g., 50% of all cars are compact and 50% are midsize). This ratio approximation is within ± 5% for cars and when considering vans in the light truck/SUV category (*16*). In calculating the overall battery charging efficiency we again mimic Kintner-Meyer et al. (*23*). They assume an 8% loss in the transmission and distribution system (*23, 25*), a battery charger efficiency of 87% (for a 240 V system), and a battery efficiency of 85%, which result in an overall charging efficiency of 68%.

2.4. Gasoline Displacement of PHEVs. In 2005, 20.7 MBBl/d of petroleum products were consumed in the U.S (*17*). Of that quantity, 9.13 MBBl/d (141 Bgal/yr) and 4.11 MBBl/d (63 Bgal/yr) was in the form of motor gasoline and distillate fuel oil (DFO) which primarily includes transportation diesel fuel. Of the gasoline consumed in the United States in 2005, 126.6 billion gallons (Bgal) was refined within the U.S., 16.8 Bgal was imported as already refined, and 2.1 Bgal was exported (Table S1, Supporting Information). Gasoline and DFOs compose 69% of the products from petroleum, and of those products, 97% of gasoline and 68% of DFO is used for transportation purposes (*17*).

In calculating the water usage associated with refining gasoline, we assume that for every gallon of crude oil refined, 0.466 gallons ends up as gasoline, with the rest in the form of DFO, paraffins, waxes, asphalt, etc. (*16, 17*). In the United States, this ratio has varied from 43.0% to 47.3% over the last few decades (*16*).

Before going into the details of how water usage changes in driving LDV PHEVs instead of pure ICE vehicles, it is useful to set the scale for the number of vehicles required to displace a certain amount of gasoline or crude oil. As stated earlier, there are approximately 234 million gasoline-powered LDVs in the United States, which puts an upper limit on how many vehicles can be PHEVs.

The following eqs 1–4 describe how we calculate the number of PHEVs required to displace a given amount of gasoline. Equation 1 shows how many miles, M, need to be driven by grid-based electric power to displace a target amount gasoline, G, in gallons

$$M = G \cdot [(\%\ \text{car miles})(\text{mpg}_{\text{cars}}) + (\%\ \text{light truck/SUV miles})(\text{mpg}_{\text{LT/SUV}})]$$

$$M = G \cdot [(0.60)(22.3) + (0.40)(17.7)] \quad (1)$$

$$M = G \cdot \text{mpg}_{\text{avg}} = G \cdot 20.46$$

where G is given or derived from barrels of crude oil using the 46.6% gasoline conversion rate and 42 gallons in a barrel. Equation 2 describes the number of PHEV-R_is needed to displace a given number of gasoline miles, M, if all R_i electric miles of the PHEV − R_i are driven

$$N_{\text{PHEV}-R_i} = \frac{(\text{gasoline miles to displace})}{(\text{range})_i} = \frac{M}{R_i} \quad (2)$$

where R_i is the all-electric range of the PHEV. For clarity, the notation PHEV40 represents vehicle with a 40-mile all-electric range, PHEV60 is for a 60-mile electric range, etc. The number of PHEVs required to drive a given number of electric miles is greater when the PHEVs are not driven their entire electric range every day. Thus, using eq 3 we calculate an alternate, but more realistic, number of PHEVs required to drive a given number of electric miles based upon the driving distribution of Figure 1:

$$N_{PHEV-R_iP_i} = M \Big/ \left[R_i(\%\ \text{of drivers driving} \geq R_i) + \sum_{j=i,i-10,...}^{i-10} D_{(j-10)\rightarrow j}\ (\%\ \text{of drivers driving}\ R_{(j-10)\rightarrow j}\ \text{miles}) \right] \quad (3)$$

where $D_{(j\text{-}10)\rightarrow j}$ is the assigned miles driven for the average driver who drives in the range from "j − 10" miles to "j" miles. For example, for the range of driving between 10 and 20 miles we assume $D_{10\text{–}20}$ = 15 miles/day. Increments of 10 are used because the data from the NHTS are available in bins of 10 miles, though smaller bins would yield more accurate information. For each bin of daily driving miles, we assume $D_{(j\text{-}10)\rightarrow j} = [(j - 10) + j]/2$, or the value in the middle of the range. However, this approximation is not strictly true, rather it is a convenient assumption. The gallons of gasoline displaced per PHEV-R_i is

$$\text{gallons of gasoline displaced/PHEV-}R_i = \frac{G}{N_{\text{PHEV}}} \quad (4)$$

where N_{PHEV} can be the result of eqs 2 or 3.

An example calculation using eqs 1−4 is as follows for a PHEV40 (i.e., R_i = 40). Using eq 1 and a target to displace 1 MBBl/d of gasoline, or 42 million gallons (Mgal), we calculate 860 million miles need to be driven daily by electric power. The number of PHEV40s to drive the daily 860 million miles if their full electric range is used, via eq 2, is 21.5 million vehicles. To calculate the number of PHEV40s using normal driver characteristics, we note that 26.8% of drivers drive at least 40 miles/day (m/d). Drivers that drive less than 40 m/d are 8.6% at 30–40 m/d, 11.5% at 20–30 m/d, 14.3% at 10–20 m/d, and 14.8% at 0–10 m/d. Inputting these values into eq 3, as shown in eq 5, shows that 44.1 million PHEV40s driven at normal driving patterns displace 42 Mgal gasoline per day. Thus, eq 4 shows the gallons of gas displaced every day per PHEV40 to be 2.0 and 1.0 for full range and normal driving patterns, respectively. Performing similar calculations shows PHEV20s displace 1.0 and 0.6 gallons/day and PHEV60s displace 2.9 and 1.2 gallons/day for full electric range and normal driving patterns, respectively.

$$N_{\text{PHEV40}} = (860\ \text{million miles}) \,/\, [(40\ \text{m/d})(26.8\%) + [(35\ \text{m/d})(8.6\%) + (25\ \text{m/d})(11.5\%) + (15\ \text{m/d})(14.3\%) + (5\ \text{m/d})(14.8\%)]] \quad (5)$$

$$N_{\text{PHEV40}} = 44.1\ \text{million}$$

Figure 2 plots the number of PHEVs with 20, 40, and 60 mile all-electric ranges that would be required to displace a certain amount of (a) gasoline and (b) crude oil. The large range of uncertainty in Figure 2 results from lack of knowledge about how PHEVs will actually be driven. The upper bounds (solid lines) of each PHEV category represent the number of PHEVs required when using eq 3, and the lower bounds (dashed lines) of each PHEV category represent the number of PHEVs required when using eq 2.

The fact that the lower bound of PHEV20 and the upper bound of PHEV40 (as well as lower bound of PHEV40 and upper bound of PHEV60) almost match exactly is coincidental. This comparison shows that each PHEV40 driven at normal driving patterns will displace approximately as much gasoline, 1 gallon/day, as a PHEV20 driven at least 20 miles (e.g., its full electric range). Thus, fleet PHEV20s driven over 20 miles per day act the same as PHEV40s driven at "normal" patterns.

2.5. Water Consumption versus Withdrawal. 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 a *concentrated* source and not directly returned. An example of water consumption is 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. Water *withdrawal* pertains to water that is taken from a *concentrated* source, used in a process, given back from whence it came, and available again for the same or other purposes. An example of water withdrawal is an open-loop cooling system for thermoelectric steam power generation that withdraws cool water from a

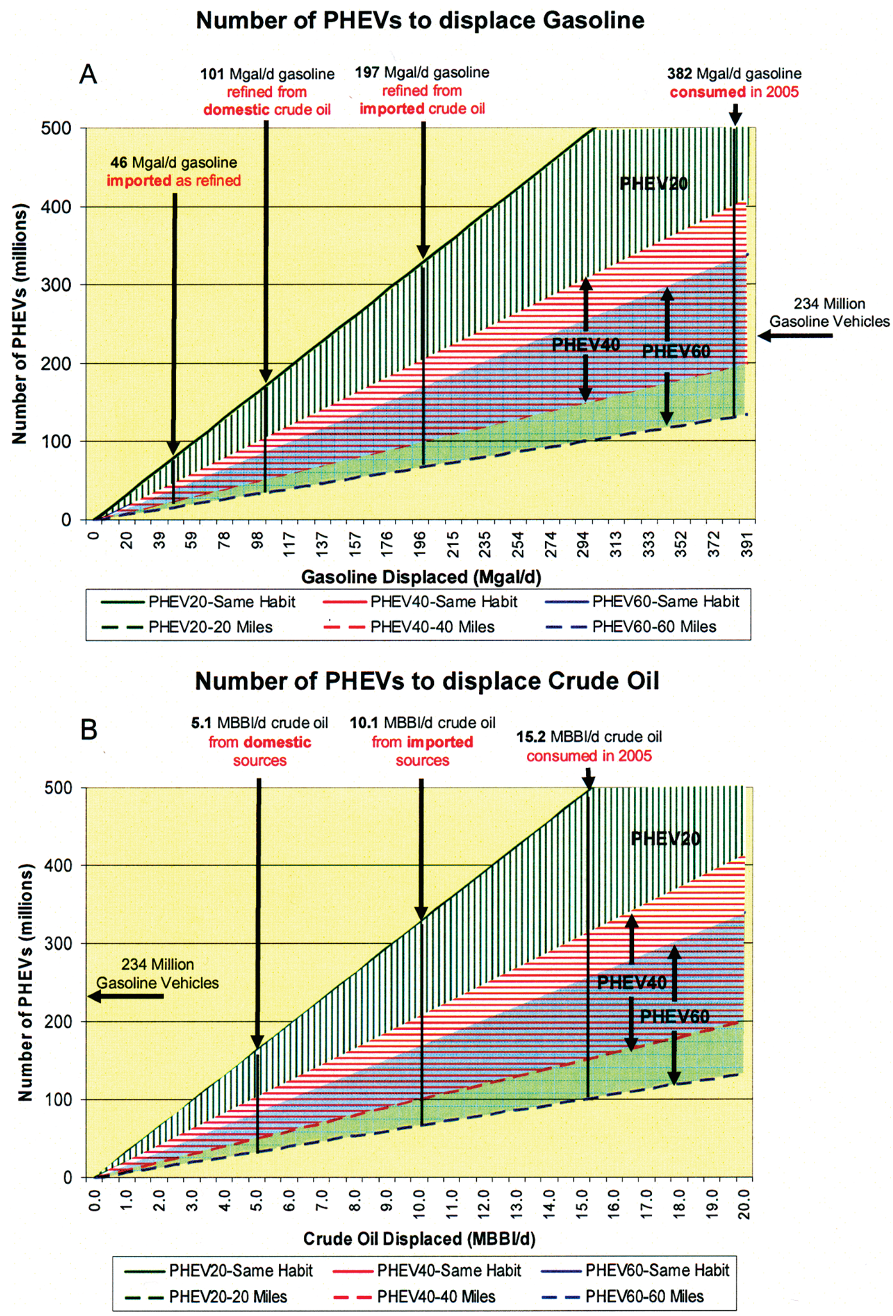

FIGURE 2. Gasoline (a) and crude oil (b) consumed in the United States in 2005 that is displaced for varying numbers of PHEVs of electric range 20, 40, and 60 miles. "Same Habit" is for PHEVs driven with the usual driving habits as shown in Figure 1. "20-Miles", "40-Miles", and "60-Miles" are for PHEVs that drive their entire daily electric range.

reservoir into its condensing unit and discharges that heated water back into the reservoir.

2.6. Water Consumed in Extracting Oil in the United States. Water consumption for oil production is only appreciable for oil wells requiring secondary or enhanced oil recovery (EOR) after the natural stored pressure of the oil field has fallen to a level that is too low for the oil to naturally flow from the reservoir. EOR reports suggest that approximately 12% of U.S. oil production is due to EOR methods, and that ratio has held roughly steady over that past decade (*31, 32*). Using the 2006 EOR Survey (*32*) along with the water consumption values of Gleick (*13*) for the various EOR techniques, we obtain an approximate water consumption of 346 Mgal/d, or 126 Bgal/yr, for 649,217 BBl/d production from EOR (Table S3, Supporting Information). Because we assume 46.6% of crude oil is refined into gasoline, we use a value of 58.8 Bgal/yr of water consumed for oil from EOR going to gasoline, or 0.42 gallons of water/gallons of gasoline averaged over all gasoline consumed in the United States.

2.7. Water Consumed and Withdrawn in Refining Gasoline. Gleick reports that approximately 525 gallons of water are withdrawn for every barrel of crude oil refined, or 12.5 gallons of water for every gallon of crude (*13*). Thus, the 17.7 MBBl/d refined in the United States in 2005 withdrew water at a rate of 9.3 Bgal/d, or 3,394 Bgal/yr.

A Department of Energy report states that 1–2.5 gallons of water are consumed for every gallon of product from the petroleum refining process (*13, 26*). The water consumption is mostly as a process fluid involved in the refining process and as a coolant for on-site thermoelectric power and exothermic reactions. In 2005 approximately 127–316 Bgal (billion gallons) of water were consumed in refining gasoline from approximately 17.7 MBBl/d of petroleum inputs. We do not include the water consumed in refining imported

TABLE 1. Water Consumption and Withdrawal Contributions for Light Duty Vehicle Travel Powered by Electricity

electric miles	water consumption (gal H_2O /kWh)	water withdrawal (gal H_2O /kWh)	% of U.S. electricity mix	water consumption for travel (gal H_2O/mile)[a]	water withdrawal for travel (gal H_2O/mile)[a]
mining and processing				≥0.09	≥0.09
coal (avg.)	0.03	≥0.03	50.8		
natural gas	0.08	≥0.08	18.6		
nuclear	0.80	≥0.80	19.3		
thermoelectric cooling (U.S. mix)	0.47	21.2	100%	0.23	10.5
total	0.65	21.4	100%	0.32	10.6

[a] To calculate gal H_2O/mile for electric miles, multiply gal H_2O/kWh by 0.336 kWh/mile (avg. for electric LDV fleet) and divide by round-trip charging efficiency of 68% (as discussed in Section 2.3).

gasoline as the required water resources existed outside of the United States and therefore are not directly related to the domestic public policy debate.

2.8. Water Consumed for Mining and Processing of Electricity Fuels. Mining fuels for electricity production is primarily for coal, uranium, and natural gas. These fuels power nearly 88% of the U.S. electricity generation, with most of the remainder from renewable sources in large part due to hydroelectric facilities (*17*). We estimate water consumption for mining and processing of coal, natural gas, and uranium using values from Gleick (*13*) and the Department of Energy (*26*).

During 2003, 70–260 Mgal/d of water (*26*) were consumed in mining of coal. This range translates to 0.013–0.048 gal/kWh of electricity to produce 51% of the U.S. 3,883 billion kWh in 2003 (*13*). Approximately 3 gal/MMBtu of natural gas is consumed for processing and pipeline operation translating to 0.08 gal/kWh for electricity that accounts for 18.6% of the U.S. 4,039 billion kWh generated in 2005. In 2005 the U.S. used 8.13 billion MMBtu (*17*) of nuclear fuel to produce 19.3% of the electricity. We assume water consumption at 5.6 gal/MMBtu for mining and 21.7 gal/MMBtu for milling and processing (*13*) of uranium to produce pellets for rod tubes used in nuclear reactors. This water consumption translates to 0.80 gal/kWh for fuel to use in nuclear reactors. Note we assume 35% thermal conversion efficiency to electricity for both natural gas and nuclear fuels, but natural gas conversion can be considerably higher (up to 60%) in combined cycle power plants.

2.9. Water Consumed and Withdrawn for Electricity Generation. When generating electricity, typically the vast majority, approximately 65% of energy content of the fuel (e.g., coal, natural gas, uranium, fuel oil) is lost in the thermoelectric conversion process as heat, for which water is the primary coolant (*17*). Thus, water withdrawal and consumption are a large part of the electricity generation process. Novel air-cooling methods exist that do not use water, but they reduce the energy conversion efficiency of the power plant, require higher up-front expenditures on capital equipment, and are consequently rarely used in the United States.

The thermoelectric power industry mainly uses two broad categories of cooling systems: (1) open-loop, or once-through, in which high flowrates of water are pumped from reservoirs or streams through heat exchangers such that almost none of the water is evaporated in the pumping cycle, and (2) closed-loop where lower flowrates of water dissipate heat by evaporation within cooling towers.

Closed-loop cooling is often used where access to a large volume of water is not available. Closed loop cooling consumes 1.5−2 times more water, but withdraws much less—by 2 orders of magnitude. Closed-loop cooling methods withdraw on the order of 0.2–1.1 gal/kWh instead of the 7.5–60.0 gal/kWh typical of open-loop methods (*26*).

In 1995 (the last year water consumption was recorded by the USGS) the thermoelectric sector consumed 1,342 Bgal (*28*), and the electricity generated by the U.S. electric power sector was 3,194 billion kWh, of which 309 billion kWh was from the renewable sources of hydroelectric, wind, and solar that do not consume water for cooling (*17*). Using the thermoelectric water consumption and electric power generated minus nonwater-consumptive methods in 1995, we obtain an average U.S. water consumption value of 0.465 gal/kWh for electricity generation.

The U.S. thermoelectric power sector water withdrawal in 2000 was 71,175 Bgal (*27*), and the electric power sector generated 3,638 billion kWh of electricity (*17*). Of that electricity, 321 billion kWh was from renewable energy, but only 6 billion kWh from wind and solar which withdraw no water. The vast majority of renewable electricity, 271 billion kWh, was from hydroelectric power which we assume does not withdraw water as it never leaves the run of the river. These values result in an average electric power water withdrawal rate of 21.2 gal/kWh. This relatively large value for water withdrawal points to the large percentage of power generated in the U.S. based upon thermoelectric processes and open-loop cooling.

The water withdrawal for thermoelectric cooling is the primary component of the calculated water withdrawal rate of 10.6 gal/mile driven electrically by PHEVs. We estimate that for electric miles driven by PHEVs, the water consumption rate due to mining and processing is 0.09 gal/mile, and the consumption rate due to thermoelectric cooling is 0.23 gal/mile.

3. Results and Discussion

The values for water used for electric and gasoline travel are displayed in Tables 1 and 2. Recall that we inherently assume the current electricity generation mix will continue even though changes will happen. Assessing the options for future electricity generation that can reduce the demand on water resources is beyond the scope of this paper. The analysis shows that electric miles powered by the current generation mix withdraw over 17 times more water and consume almost 3 times more water than miles powered by gasoline. Also water consumption as a percentage of water withdrawal is 3% for electric miles and 11%–22% for gasoline miles.

3.1. Water Usage for Electron (PHEV) Automotive Economy. The typical U.S. driver would drive 4,500, 7,100, and 8,600 electric miles per year in a PHEV20, PHEV40, and PHEV60, respectively. For example, it takes 114, 72, and 59 million PHEV20, PHEV40, and PHEV60, respectively, to drive 500 billion electric miles annually (Figures S2 and S3, Supporting Information). Since there are 234 million gasoline LDVs on the road today, displacing one-sixth to one-fifth of gasoline miles with 114 million PHEV20s, or 49% of the vehicle fleet, sounds feasible, but with annual sales rates of cars and

TABLE 2. Water Consumption and Withdrawal Contributions for Light-Duty Vehicle Travel Powered by Gasoline

gasoline miles	water consumption (gal H_2O/gal)	water withdrawal (gal H_2O/gal)	water consumption for travel (gal H_2O/mile)[a]	water withdrawal for travel (gal H_2O/mile)[a]
mining			0.02	0.02
oil (EOR and non- EOR)	0.42	≥0.42		
refining	1.0–2.5	12.5	0.05–0.12	0.61
total	1.4–2.9	12.9	0.07–0.14	0.63

[a] To calculate gal H_2O/mile for gasoline miles, divide gal H_2O/gal of gasoline by the average mileage of the U.S. light duty vehicle fleet, 20.46 mpg, as calculated in eq 1.

light trucks/SUVs amounting to 17 million vehicles per year, it would take 7 years if every vehicle sold were a PHEV20 (*16*). Comparing the displacing of the same 500 billion gasoline miles with electric miles of PHEV60s requires replacement of 25% of cars, light trucks, and SUVs, for which the tradeoff would be annual water consumption of 160 Bgal/yr compared to 35–70 Bgal/yr using gasoline. Also, 5,300 Bgal/yr would be withdrawn instead of 300 Bgal/yr. These increases in water usage represent approximately 0.2–0.3% (*28*) and 3% (*27*), respectively, of overall U.S. water consumption (100,000 Mgal/d freshwater in 1995) and withdrawal (408,000 Mgal/d in 2000).

3.2. Policy Implications of Electron Auto Economy. This water usage for converting transportation of light-duty vehicles from gasoline to electric presents a 3-fold increase in water consumption, but a 17-fold increase in water withdrawal. The need for access to cooling water during electricity generation is large. Water rights and access are also largely a regional issue due to varying laws, rain patterns, river paths, and groundwater supply. Thus, in order to implement the electron automotive economy where a substantial number of miles are driven electrically, the water demands need to be assessed on a regional basis. This means that some relatively wet regions of the United States may be able to support more PHEVs at lower cost than other relatively dry regions. Also, dry regions can focus on cooling techniques that require little water or electricity generation technologies, such as wind and photovoltaic solar that do not consume and withdraw water. Most importantly, public policy decisions that promote PHEVs or electric vehicles need to consider the impact on water resources beforehand because the increased demand for water withdrawals is potentially quite substantial and could impact water availability or rights for irrigation, municipal, and other competing purposes.

There are several steps and policies that can be promoted to enable sufficient water access for enhancing PHEV market success.

1. *Promote research and development of distributed generation and renewable energy sources* that use little to no water and can possibly be located onsite where PHEVs are charged. PHEVs provide storage for intermittent generation such as wind power that often tends to generate a large proportion of power at night when winds blow more in many regions of the country.

2. *Develop regional water plans* that consider increased demands for electricity for PHEVs in order to ensure adequate water access in light of competing water demands for municipal and irrigation uses. These regions and their governing policies should be defined by the geography and supply of water resources (e.g., river basins, reservoirs, and aquifers), not political boundaries. Also, water plans must consider precipitation patterns and their expected and unexpected changes over time (for example due to climate change). Starting with this information, regional water districts can assess priorities during water shortages. For example, if water restrictions are needed and transportation uses more regional water (as opposed to water near oil refineries) in the future, should driving always be excluded from rationing while focusing on reducing water usage in lawn watering, car washing, and other traditionally restricted areas of usage?

3. *Move to generate more electricity by methods that do not withdraw such large amounts of water.* These methods include a move to closed-loop cooling systems at thermoelectric plants, air-cooling systems, and so forth. Some current and pending rules of the Environmental Protection Agency regarding water intake velocities and protection of aquatic life almost necessitate the used of closed-loop cooling for thermoelectric plants (*29, 30*).

4. *Use reclaimed, saline, or other water sources* that are suitable for thermoelectric cooling, but unsuitable or unable to be treated economically for drinking.

Overall, we conclude that the impact on water resources from a widespread shift to grid-based transportation would be substantial enough to warrant consideration for relevant public policy decision-making. That is not to say that the negative impacts on water resources make such a shift undesirable, but rather such impacts should be quantified ahead of time to avoid unnecessary conflicts due to potential water shortages.

Supporting Information Available

Table of water usage for enhanced oil recovery; figures plotting and comparing water withdrawal and consumption for electric and gasoline travel; statistics for gasoline and distillate fuel oil refining, importing, and exporting in the U.S; and a cumulative distribution of driving frequency versus distance traveled by U.S. drivers. This information is available free of charge via the Internet at http://pubs.acs.org.

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ES0716195