Environmental Science & Technology

Policy Analysis

pubs.acs.org/est

Potential for Electrified Vehicles to Contribute to U.S. Petroleum and Climate Goals and Implications for Advanced Biofuels

Paul J. Meier,[†] Keith R. Cronin,[†] Ethan A. Frost,[†] Troy M. Runge,*[,†,‡] Bruce E. Dale,[§] Douglas J. Reinemann,[†,‡] and Jennifer Detlor[†]

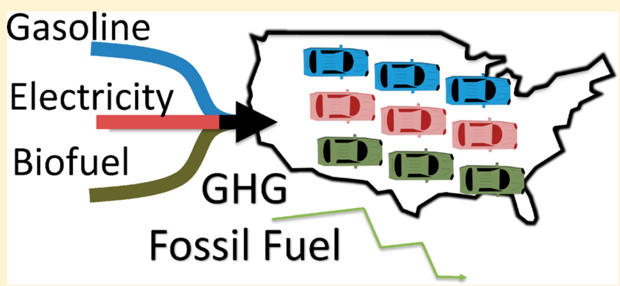
[†]Great Lakes Bioenergy Research Center and Wisconsin Energy Institute, University of Wisconsin—Madison, 1552 University Avenue, Madison, Wisconsin 53706, United States

[‡]Biological Systems Engineering Department, University of Wisconsin—Madison, 460 Henry Mall, Madison, Wisconsin 53706, United States

[§]Biomass Conversion Research Laboratory, Department of Chemical Engineering and Material Science, and Great Lakes Bioenergy Research Center, Michigan State University, 3815 Technology Boulevard, Suite 1045, Lansing, Michigan 48910, United States

Supporting Information

ABSTRACT: To examine the national fuel and emissions impacts from increasingly electrified light-duty transportation, we reconstructed the vehicle technology portfolios from two national vehicle studies. Using these vehicle portfolios, we normalized assumptions and examined sensitivity around the rates of electrified vehicle penetration, travel demand growth, and electricity decarbonization. We further examined the impact of substituting low-carbon advanced cellulosic biofuels in place of petroleum. Twenty-seven scenarios were benchmarked against a 50% petroleum-reduction target and an 80% GHG-reduction target. We found that with high rates of electrification (40% of miles traveled) the petroleum-reduction benchmark could be satisfied, even with high travel demand growth. The same highly electrified scenarios, however, could not satisfy 80% GHG-reduction targets, even assuming 80% decarbonized electricity and no growth in travel demand. Regardless of precise consumer vehicle preferences, emissions are a function of the total reliance on electricity versus liquid fuels and the corresponding greenhouse gas intensities of both. We found that at a relatively high rate of electrification (40% of miles and 26% by fuel), an 80% GHG reduction could only be achieved with significant quantities of low-carbon liquid fuel in cases with low or moderate travel demand growth.



INTRODUCTION

Energy independence has been a stated goal of every U.S. president since Richard Nixon.[1] Annual U.S. crude oil imports have roughly tripled since this goal was stated in 1973, however, and now comprise about half of U.S. petroleum supply.[2] Climate change presents a second daunting challenge. An 80% reduction in U.S greenhouse gas (GHG) emissions by 2050 has been generally established as the de facto required domestic contribution to stabilizing global concentrations at low to medium levels, that is, 450 and 550 ppm carbon dioxide equivalent (CO_2-equiv).[3] In their "New Energy for America" plan, President Obama and Vice President Biden reiterated the "80by50" goal (relative to 1990) to "address the global climate crisis", while also proposing to end U.S. "addiction to foreign oil".[4] Within the transportation sector, the two basic options for reducing petroleum use and greenhouse gas (GHG) emissions are fuel-use reduction and fuel substitution. Working counter to fuel-use reduction, vehicle-miles traveled (VMT) on U.S. roadways has nearly doubled (94% increase) between 1980 and 2012.[5] As miles of travel increase, improved vehicle efficiency offers a second approach for reducing fuel demand and emissions. Recent fuel economy standards[6] propose to increase fleet-wide passenger cars and trucks efficiency to 40.9 mpg in model year 2021, and 49.6 mpg in model year 2025, and Winkler et al.[7] assert that these standards, along with CO_2 regulations through 2025, are consistent with a global CO_2 stabilization concentration of 450 ppm.

Hydrogen is not envisioned to be a major contributor in the near term because of techno-economic limitations leaving natural gas, liquid biofuel, and electricity as candidates to meet the dual national goals of replacing oil and reducing GHG emissions. While natural gas has occasionally proven to be a cost-effective alternative for trucking, its GHG benefits relative to petroleum fuels are limited.[8] Bioenergy's potential to reduce petroleum dependence and GHG emissions were both motivating factors for the Renewable Fuels Standard's (RFS) target for 16 billion gallons of cellulosic biofuel with regulated

Received: October 23, 2014
Revised: June 2, 2015
Accepted: June 18, 2015
Published: June 18, 2015

DOI: 10.1021/acs.est.5b01691
Environ. Sci. Technol. 2015, 49, 8277–8286

GHG intensity at 60% less than gasoline.[9] Meeting the RFS goal by the 2022 date seems increasingly unlikely, however, as 2013 production requirements were dramatically reduced to only 14 million gallons.[10] Given the current barriers to increasing ethanol-based biofuels (blend wall, slow growth in cellulosic biofuel production, regulatory uncertainty surrounding the RFS), transportation electrification seemingly offers a more immediate opportunity to displace gasoline. Electrified vehicles (meaning all of hybrid, plug-in hybrid, or battery electric technologies) could largely replace conventional gasoline vehicles, under favorable conditions (e.g., consumer attitudes, fuel prices, battery technology advancement, vehicle costs and subsidies). The likelihood of these conditions being met is speculative, however, and projections for consumer adoption of electrified vehicles have varied widely.

We are interested in the extent to which electrified vehicles could reduce petroleum consumption and greenhouse gas (GHG) emissions and the sensitivity of these impacts across a range of travel demand and technology scenarios. We find that petroleum consumption and GHG emissions are highly sensitive to these inputs, with resulting petroleum consumption and GHG emissions varying widely. The implication for biofuels is important, to the extent they are aimed at meeting climate and petroleum use reduction goals. To put these implications into perspective, we further estimate the volume of RFS-compliant advanced biofuel (e.g., cellulosic biofuel) needed to meet petroleum and climate goals.

■ METHODOLOGY

This work was aimed at estimating national fuel and emissions impacts from increasing reliance on electrified light-duty transportation, and the resulting implications for advanced biofuels. To investigate future vehicle fuel consumption and emissions, we consider the future composition of the entire U.S. auto fleet, and the associated fuel sources, fuel efficiency, and greenhouse gas impact for each vehicle type and vintage. We reconstructed the vehicle technology portfolios from two national vehicle studies, comparing their fuel and emissions impacts under normalized assumptions, variable travel demand growth, and a range of increasing electrification. Subsequently, we estimate the hypothetical volume of RFS-compliant cellulosic biofuel, necessary to meet potentially desirable U.S. petroleum and GHG objectives. We do not look at any specific policy in particular, but rather the more general goals to reduce petroleum consumption by half (imported oil has comprised 40−60% of U.S. consumption since about 1990) and to reduce GHG by 80%. In this work, we measure potential reductions against a 2011 baseline. We treat the cellulosic biofuel contribution hypothetically, both in terms of volume and in GHG intensity. We assume that all advanced biofuels are in compliance with RFS-regulated greenhouse gas intensity, and we do not presuppose a biofuel resource limit. In other words, we calculate the volume that would satisfy the objective exactly, using hypothetical RFS-compliant fuel, without regard for underlying biomass resource potential. Our approach is detailed in the following methodology discussion, divided into Scenario Development, Fleet Simulation, and Emissions Accounting sections. Additionally a table with the primary assumptions used is shown in Table S1, Supporting Information.

Scenario Development. Many recent studies have examined electrified and alternative vehicle technologies, comparing relative rates of fuel consumption and greenhouse gas emissions.[7,11−22] Lipman and Delucchi[23] provide an extensive summary of relevant literature prior to 2010. Most of these studies provide side-by-side comparisons of alternative vehicle technologies using a life-cycle assessment (i.e., well-to-wheels) approach.

To estimate the U.S. national impacts of electrified vehicles, more in-depth than the literature, we are primarily interested in studies which comprehensively evaluate electrified vehicle market penetration across the entire U.S. automobile market, on a regional basis. In its 2007 *Environmental Assessment of Plug-In Hybrid Electric Vehicles* (EPRI-NRDC Study), the Electric Power Research Institute and Natural Resources Defense Council touted their report as "the most comprehensive environmental assessment of electric transportation to date".[24] Looking at low, medium, and high scenarios for electrified vehicle penetration, the EPRI-NRDC study concluded that "each region of the country will *yield reductions* (emphasis added) in GHG emissions" from 2010−2050. A subsequent 2009 study by Argonne National Laboratory, the *Multi-Path Transportation Futures* (ANL Study),[25] compared "alternative ways to make significant reductions in oil use and carbon emissions from U.S. light vehicles from now to 2050". Contrary to the EPRI-NRDC Study, the ANL Study forecast much lower adoption of hybrid and electric vehicles, resulting in *net increases* in fuel use and GHG emission by 2050, as fleet efficiency improvements were outweighed by the assumed growth in travel demand (the ANL Study's "PHEV and Ethanol" scenario is most relevant to this work). While we found these studies to be the most comprehensive of their kind, they disagreed greatly in regard to petroleum and GHG impacts, stemming from very different rates of vehicle electrification and travel demand growth that each study assumed. Further, these studies did not offer significant sensitivity analysis, making it difficult to extend their conclusions to alternative scenarios. As discussed below, we recreated and normalized the highly detailed vehicle assumptions and transport calculations from these studies, so that we might provide significant sensitivity analysis across a much broader range of future scenarios.

Both the ANL and EPRI-NRDC study efforts explicitly modeled consumer choice to forecast future portfolios of vehicle technologies. The ANL effort incorporated rigorous vehicle cost modeling and used economic modeling to estimate how vehicle and fuel prices would influence consumer adoption. Similarly, the EPRI-NRDC study states that vehicle market shares were "developed from choice based market modeling of customer preference." Neither the ANL nor EPRI-NRDC study forecast appreciable penetration of electric-only vehicles. Rather, the electrified vehicle market was comprised of two technology types: hybrid electric vehicles (HEVs use only petroleum fuel but receive electric assistance via regenerative braking) and plug-in hybrid electric vehicles (PHEVs use both petroleum and electricity fuels).

The magnitude of electrified vehicle penetration in the ANL Study (38%) was consistent with the "Low Penetration" scenario in the EPRI-NRDC study (44%), however, the EPRI-NRDC Study forecast dramatically higher adoption of electrified vehicles in its Medium (86% combined) and High (95% combined) Penetration scenarios. The studies forecast very different vehicle portfolios (i.e., distribution between HEV, PHEV, BEV technologies). In the ANL Study, the electrified vehicle market was forecast as almost entirely HEV technology (using liquid fuels only), corresponding to only 0.3% of miles traveled powered by grid-derived electricity (100% of BEV and 50% PHEV miles). In the EPRI-NRDC High Penetration

DOI: 10.1021/acs.est.5b01691
Environ. Sci. Technol. 2015, 49, 8277−8286

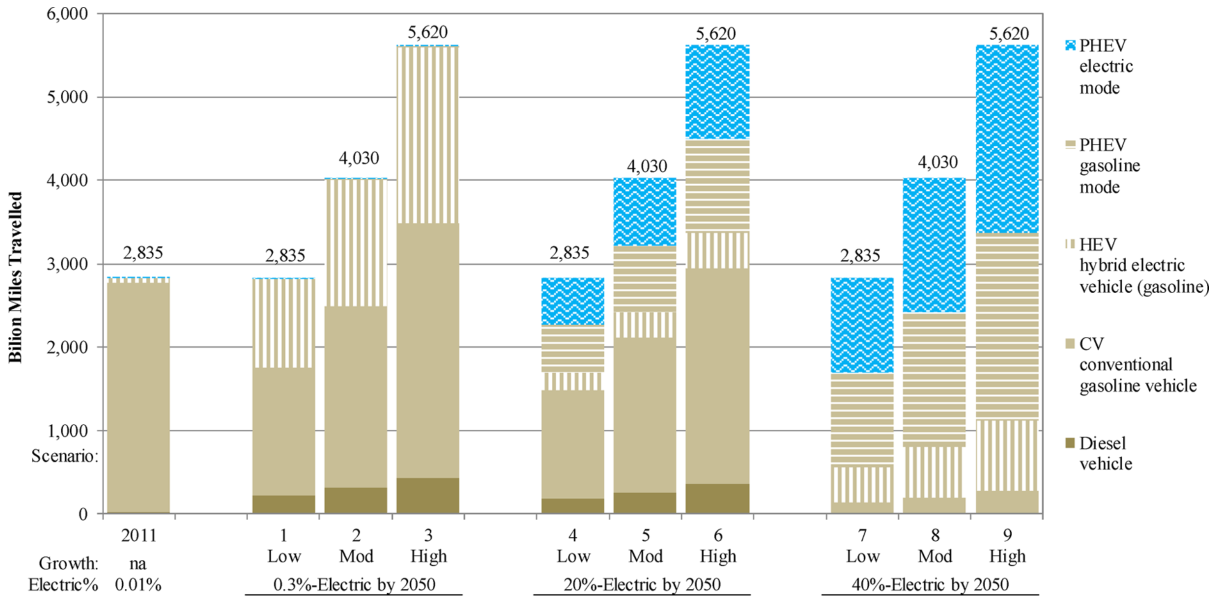


Figure 1. 2050 miles driven by vehicle technology type for 12 scenarios, reflecting three levels of increasing electrification and low, moderate, and high growth in travel demand. Scenario 3 is a recreation of the ANL Study,[25] and scenario 8 is a recreation of the EPRI-NRDC Study.[24]

scenario, 80% of vehicle market share was forecast as PHEV technology and 15% as HEV, corresponding to 40% of miles traveled powered by grid-derived electricity. It should be noted that recent trends are already proving the ANL forecast too pessimistic, with PHEV and BEV representing 0.6% of vehicle sales in February 2015.[26]

Given the broad range of their electrified vehicle market forecasts, the EPRI-NRDC and ANL Studies provide excellent bookends for comparing minimal and maximal electrification of passenger transportation. As shown in Figure 1, we based our low electrification (0.3% electric powered miles) on the ANL Study's[25] "PHEV and Ethanol" scenario, and we based our high electrification (40% electric-powered miles) on the EPRI-NRDC Study's[24] High scenario with 95% electrified vehicles. In addition, we consider intermediate (20% electric-powered miles) electrification halfway between the high and low. In all scenarios, we assumed the same technology distribution (e.g., shares HEV, PHEV) for passenger trucks and passenger cars. As shown in Figure 1, we examine each of these three vehicle mixtures under low, medium, and high growth assumptions for travel demand (discussed below). These nine combinations represent reference scenarios with defined fuel requirements and GHG emissions. Additionally, these same vehicle combinations and growth rates are used to examine nine petroleum-targeted scenarios and nine GHG-Targeted scenarios, as summarized in Table 1.

Fleet Simulation. Fuel and emission impacts are determined by four primary considerations: (1) the total travel demand, (2) the vehicle mix that satisfies this demand, (3) the vehicle efficiency assumptions that determine fuel requirements, and (4) the GHG intensity of the vehicles' fuels. We used a spreadsheet-model to simulate each of these considerations over time, for each vehicle type and vintage as discussed below.

Total travel demand is an enormously important assumption in estimating national fuel and emissions impacts. The ANL study based its vehicle miles traveled (VMT) on the 2007 Annual Energy Outlook (AEO) projection for 1.77%/year growth rate. Less dramatic VMT growth was projected in the most recently available AEO2014 prerelease (0.91%/year). This 2014 projected growth rate is nearly identical to historic growth in VMT, which has increased at 0.89%/year between 1999 and 2010, according to Federal Highway administration

Table 1. Summary of 27 Scenarios for U.S. Light Duty Transportation

scenario	VMT Growth (percent per year)	electricity (percent of 2050 miles)	reduction objective
	reference scenarios		
1	low 0%	0.3%	none
2	mod 0.9%	0.3%	none
3	high 1.8%	0.3%	none
4	low 0%	20.0%	none
5	mod 0.9%	20.0%	none
6	high 1.8%	20.0%	none
7	low 0%	40.0%	none
8	mod 0.9%	40.0%	none
9	high 1.8%	40.0%	none
	petroleum-targeted scenarios		
10	low 0%	0.3%	50% petrol.
11	mod 0.9%	0.3%	50% petrol.
12	high 1.8%	0.3%	50% petrol.
13	low 0%	20.0%	50% petrol.
14	mod 0.9%	20.0%	50% petrol.
15	high 1.8%	20.0%	50% petrol.
16	low 0%	40.0%	50% petrol.
17	mod 0.9%	40.0%	50% petrol.
18	high 1.8%	40.0%	50% petrol.
	climate-targeted scenarios		
19	low 0%	0.3%	80% GHG
20	mod 0.9%	0.3%	80% GHG
21	high 1.8%	0.3%	80% GHG
22	low 0%	20.0%	80% GHG
23	mod 0.9%	20.0%	80% GHG
24	high 1.8%	20.0%	80% GHG
25	low 0%	40.0%	80% GHG
26	mod 0.9%	40.0%	80% GHG
27	high 1.8%	40.0%	80% GHG

DOI: 10.1021/acs.est.5b01691
Environ. Sci. Technol. 2015, 49, 8277−8286

statistics.[27] Therefore, we used 0.9%/year VMT growth to represent "Moderate" annual change in travel demand. Using this rate and starting from 2010 VMT (2,690 billion miles), VMT grows 48% (to 3 980 billion miles) by 2050. We also considered low and high cases for travel demand, at 0% annual growth and 1.8% annual growth (as in ANL Study), respectively. We apply the growth rates uniformly to each of the 50 U.S. states, ignoring any demographic trends, which may influence regional travel demand. The market penetration over time for each of these four technology-mix scenarios, assuming moderate growth in vehicle miles traveled is shown Figure S1, Supporting Information.

To characterize the vehicle mix (i.e., portfolio of vehicle technologies and vintages), we started with the 2010 vehicle composition for each of the 50 U.S. states, based on FHWA state-level data for total passenger cars and passenger trucks.[28] In response to travel demand growth and vehicle decay, the model stepped through each subsequent year and added the necessary influx of new vehicles, conforming to the scenario's defined trajectory of electrification. We assumed the state-specific ratio of passenger cars to passenger trucks remains constant over the study period. Using this approach, we created a state-specific vehicle inventory by vehicle type and vintage. The average annual miles traveled for each vehicle type and vintage typically decline over time and an increasing proportion are retired. We accounted for age-based vehicle decay in both travel mileage and survival, assuming that existing and future vehicles adhere to mileage and survival formula shown in eq 1, using parameters reported by the National Highway Traffic Safety Administration, see Table S2, Supporting Information.[29]

$$\text{estimated survival rate} = 1 - \text{EXP}[-\text{EXP}(A + B \times \text{age})] \qquad (1)$$

Fuel consumption estimates are dependent on the travel demand in combination with technology and vintage-specific fuel efficiency. Our assumed vehicle efficiency for existing vehicles (model years 1980 through 2010) was based on average U.S. light duty vehicle fuel efficiency reported by the U.S. Department of Transportation.[30] Using these historic fuel-efficiencies, in combination with the state-specific vehicle inventories (discussed above), we estimated fuel requirements for 2010 by state and compared the estimates to reported values. See Figure S2, Supporting Information, which indicates the simulated fuel requirements are similar to historic fuel consumption data for 2010 on a state by state basis.[31] Therefore, the 2010 simulated fleet is used as the baseline for simulating future fleet evolution, from 2011 to 2050.

Assumptions for future improvements of vehicle fuel efficiency over time were based on average rates of technology advancement from the ANL Study, which required that each technology meet the same core set of performance standards. Table 2 lists the assumed 2010 vehicle efficiency and the 2050 vehicle efficiency, between which we assumed a linear rate of improvement. Importantly, we assume that these fuel efficiencies represent the actual rates achieved in on-road transport, not simply a vehicle rating. We assume vehicle fuel efficiency remains constant on an energetic basis (miles/MJ) regardless of biofuel blend. Our assumption (to remain consistent with the ANL study) is that all post-2020 vehicles are flex fuel vehicles (FFV). For future scenarios involving advanced biofuels, cellulosic biofuel is substituted for E10 gasoline on an energy basis. While the FFV is designed to consume any ethanol blend up to E85 (85% bioethanol), there is no limitation in vehicle use of "drop-in" biofuels up to 100%. To simplify the fuels accounting, we treat cellulosic biofuel as 100% bioderived drop-in fuels (i.e., not requiring a base derived from gasoline stocks). As such, post-2020 vehicles would not be required to be FFVs, as assumed here.

Table 2. Vehicle Fuel Efficiency Advancement Assumptions

		passenger cars		passenger trucks	
vehicle type	year	liquid mode (mi/gal)	electric mode (mi/kWh)	liquid mode (mi/gal)	electric mode (mi/kWh)
conventional gasoline vehicle (CV)	2010	32.9		25.7	
	2050	39.6		30.9	
diesel vehicle	2010	40.9		31.9	
	2050	47.4		37.0	
hybrid electric vehicle (HEV)	2010	50.6		37.7	
	2050	70.9		50.3	
plug-in hybrid electric vehicle (PHEV)	2010	51.9	3.51	37.2	3.08
	2050	76.4	4.58	49.4	3.90

For parallel PHEVs, as we assume here, both the engine and electric motor propel the vehicle under most driving conditions. To estimate PHEV fuel requirements, however, we must assume the fraction of miles driven in charge-depleting mode (using electricity) and charge-sustaining mode (using petroleum). Consistent with the ANL Study, we assumed 50% of PHEV travel is powered by electricity. In addition to the electricity that powers the electrified vehicle, electricity losses occur at the vehicle charger, as well as throughout the transmission and distribution system. We assumed 15% electricity losses at the vehicle charger and 6.5% throughout the transmission and distribution system, based on default assumptions in the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) model.[32] The product of these losses, $(0.85 \times 0.935)^{-1}$, translates to an additional 26% of electricity required in excess of the vehicle's consumption.

Emissions Accounting. We estimated GHG emissions from the following sources: direct vehicle-fuel combustion, power plant emissions (from electrified vehicle charging demands), and "upstream" life-cycle contributions from the petroleum fuel-cycle, and electricity fuel-cycle. Table 3 lists the assumed GHG intensity for each vehicle fuel, based on 100-year carbon-dioxide equivalence for carbon dioxide (1), methane (34), and nitrous oxide (298).[33] With the exception of power plant emissions (discussed below), emission rates are derived from the GREET model. We used 2020 default parameters from the GREET fuel-cycle spreadsheet (version 1_2013) to

Table 3. Assumed Fuel Greenhouse Gas Intensity

	greenhouse gas intensity (g CO_2-equiv/MJ)		
fuel source	vehicle fuel	fuel life-cycle	total
diesel	75.8	24.1	100.0
E10 gasoline	73.1	22.0	95.1
cellulosic biofuel	(NA, total assumed 40% of gasoline)		38.1
current electricity	153.2	15.1	168.4
80% decarbonized electricity (nationally averaged)	30.6	5.6	36.2

DOI: 10.1021/acs.est.5b01691
Environ. Sci. Technol. 2015, 49, 8277−8286

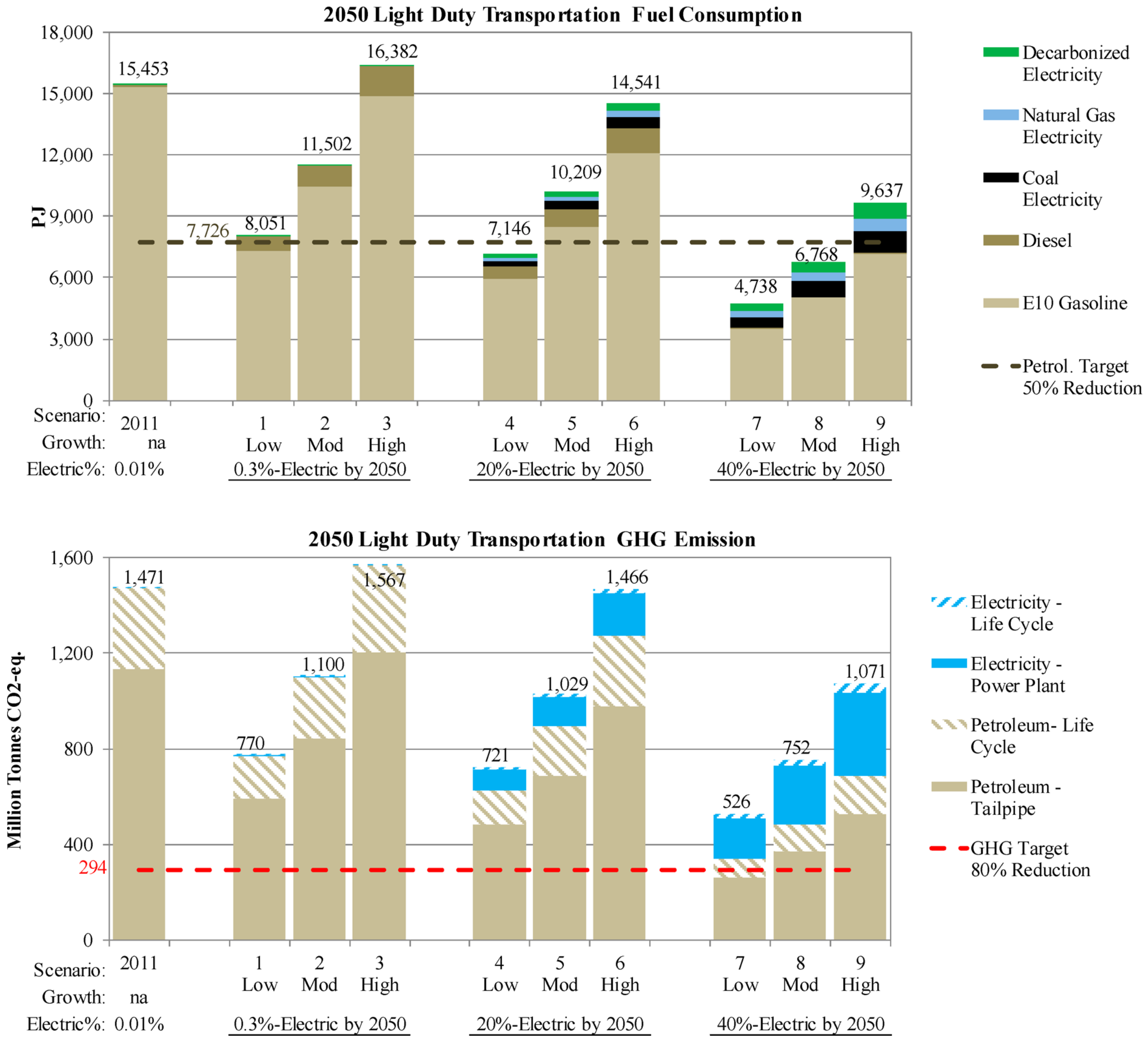


Figure 2. Nine reference case scenarios based on three levels of increasing electrification and three levels of VMT growth and assuming GHG-intensity of electricity supply remains at current levels.

estimate the GHG intensity of vehicle fuels, as well as emissions occurring during fuel production and distribution. We assume that all gasoline is E10 (i.e., 10% ethanol) and that, consistent with GREET's default parameters, 100% of ethanol supply is derived from corn. Importantly, this means that our assumed volume of the corn ethanol used in U.S. motor fuel increases and decreases in proportion to gasoline use. Similarly, oil-sand-derived bitumen contributions are assumed to remain at a constant 13.9% of petroleum feedstock, based on GREET's default assumption for 2020. These simplifications neglect the fact that future contributions from corn ethanol and oil-sand-petroleum to gasoline supply will be determined by relative market prices, including competition with E85.

We assume cellulosic biofuel's GHG intensity is exactly 40% that of E10 gasoline. This life-cycle embodied GHG content is established by the Renewable Fuel Standard (RFS) as part of U.S. Energy Independence and Security Act of 2007. As regulated by the U.S. EPA[34] only biofuels meeting a 60% reduction in GHG intensity (relative to gasoline and including indirect land use change) qualify as cellulosic biofuels toward rule compliance. The science, system boundaries, and accounting approaches used to certify these fuels are sources of considerable uncertainty and debate. Our assumption, therefore, presumes that ample time and effort improves the current state of understanding as it relates to real world production systems, including indirect effects. In this case, the existing regulatory limit for advanced biofuels is the most appropriate GHG-intensity for consideration. Because we consider only RFS-compliant biofuels, exactly meeting the 60%-GHG reduction benchmark, our advanced biofuels estimates represent the maximum required volume of RFS-compliant fuels. If future production systems were over-compliant (greater than 60% reduction), the associated biofuel contributions (i.e., to meet GHG goals) would diminish.

We assumed constant emission factors for the 2010–2050 study period, with the exception of electricity emissions. Electricity GHG intensity shown in Table 3 shows the current nationally averaged rate (U.S. EPA[35]); however, state-specific electricity emissions were calculated based on a unique electricity fuel mix and transport demand for each U.S. state. We considered three levels of GHG-intensity for U.S. electricity supply. The reference case scenarios assume no change to GHG intensity from current levels. The petroleum-targeted scenarios assume that electricity supply is decarbonized by 40%

DOI: 10.1021/acs.est.5b01691
Environ. Sci. Technol. 2015, 49, 8277–8286

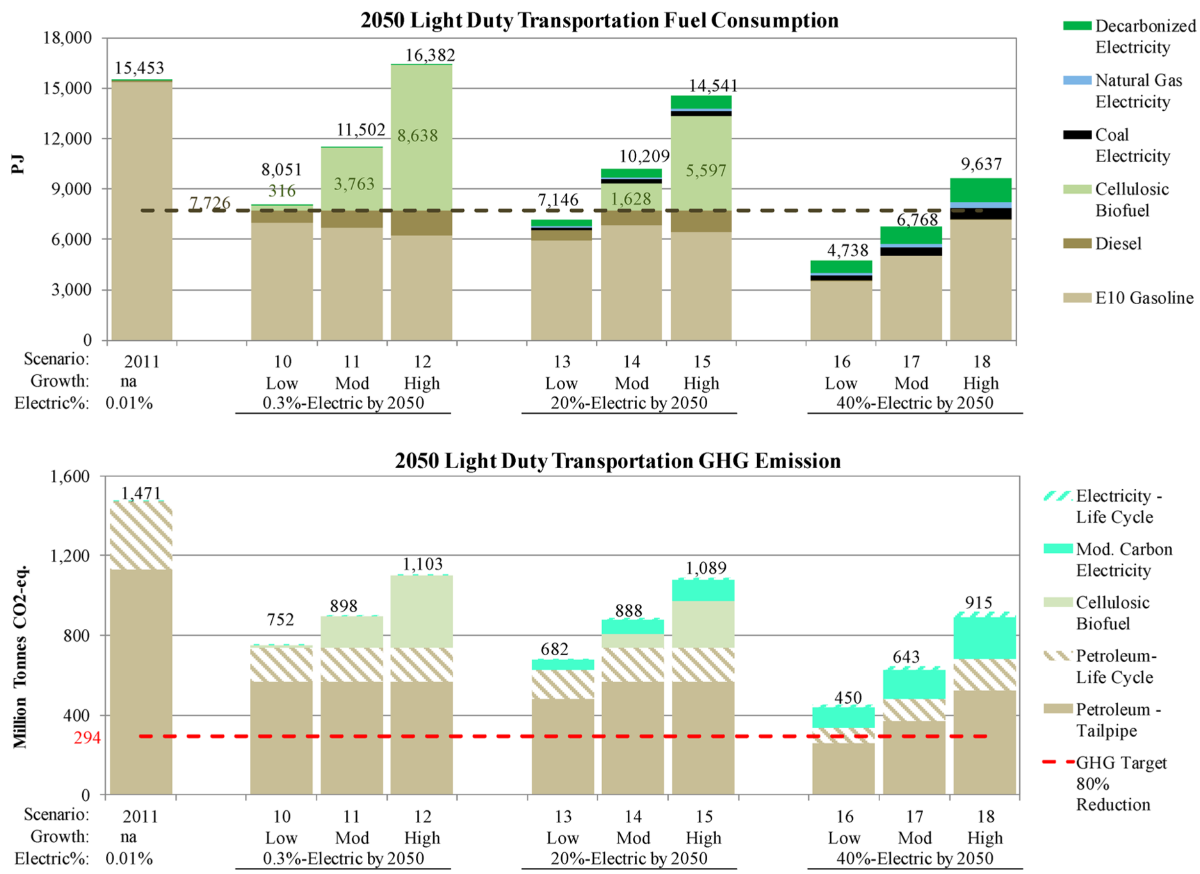


Figure 3. Nine petroleum-targeted scenarios, hypothetically substituting RFS-compliant cellulosic biofuel for gasoline until petroleum is reduced to 50% of 2011 levels and assuming a 40% reduction in electricity GHG intensity.

(i.e., emissions from fossil fuel power plants are 60% that of the reference case). The climate-targeted scenarios assume that electricity supply is decarbonized by 80% (i.e., emissions from fossil fuel power plants are 20% that of the reference case). Decarbonized electricity assumes the GHG intensity decreases linearly between 2010 and 2050, relative to each state's initial electricity emissions. In the climate-targeted scenarios, we assumed that electrified vehicles receive their electricity from an 80% decarbonized electricity grid. Upstream emissions for electricity (e.g., power plant construction and fuel production) were based on GREET's life-cycle emission rates for power plant fuel-cycle and infrastructure.[32] We considered state-specific contributions from nine generating technologies: coal, oil, natural gas, hydro, biogas, geothermal, nuclear, wind, and solar. For each generation type, we estimated "up-stream" life-cycle emissions using the GREET model. For the 80% decarbonized scenarios, we assumed that coal, oil, and gas generation declined uniformly between 2010 and 2050 that the resulting gap was filled by nuclear, wind, and solar power (48%, 48%, and 4% respectively). Contributions from hydro, biogas, and geothermal were held constant, as these technologies are potentially resource constrained and their state-specific resource availability was not considered.

We used an attributional approach to emissions allocation, meaning that we assign all electricity-sector emissions uniformly to all electricity end-uses. In other words, we assumed that electricity supply to electrified vehicles is represented by the average GHG intensity across all generation sources (see Kaufman et al.[36] for further discussion on attributional versus consequential emissions accounting). This approach does not consider the timing of vehicle charging. A more sophisticated approach could consider charge-timing profiles[37] and apply average hourly emission rates (e.g., using U.S. EPA's CAMD database[38]). We recommend this more rigorous approach for future consideration, allowing for environmental comparison of various charging strategies.

RESULTS AND DISCUSSION

In total, we examined petroleum consumption and GHG sensitivity across 27 scenarios for light duty transportation, with the 2050 results summarized in Figures 2−4. The reference scenarios (Figure 2) show the 2050 energy and GHG results for three levels of increasing electrification and three rates of VMT growth (9 scenarios) without any contributions from cellulosic biofuel. Petroleum-targeted scenarios (Figure 3) and climate-targeted scenarios (Figure 4) also include 9 scenarios each, satisfying the same travel demands with the same vehicle mixes, but substituting cellulosic biofuel for gasoline to meet the respective petroleum or GHG targets. The petroleum-targeted and climate-targeted scenarios assume a 40% and 80% reduction in fossil fuels used for electricity, respectively.

Reference Scenarios. The energy requirements for the Reference Scenarios are shown by source at the top of Figure 2 in Petajoules (PJ). We see that petroleum requirements (gasoline and diesel) in four scenarios (4, 7, 8, and 9) are below the 7726 PJ petroleum target, and another (scenario 1) is only slightly above the target. None of the reference scenarios, however, meet the GHG target for an 80% reduction, shown in

DOI: 10.1021/acs.est.5b01691
Environ. Sci. Technol. 2015, 49, 8277−8286

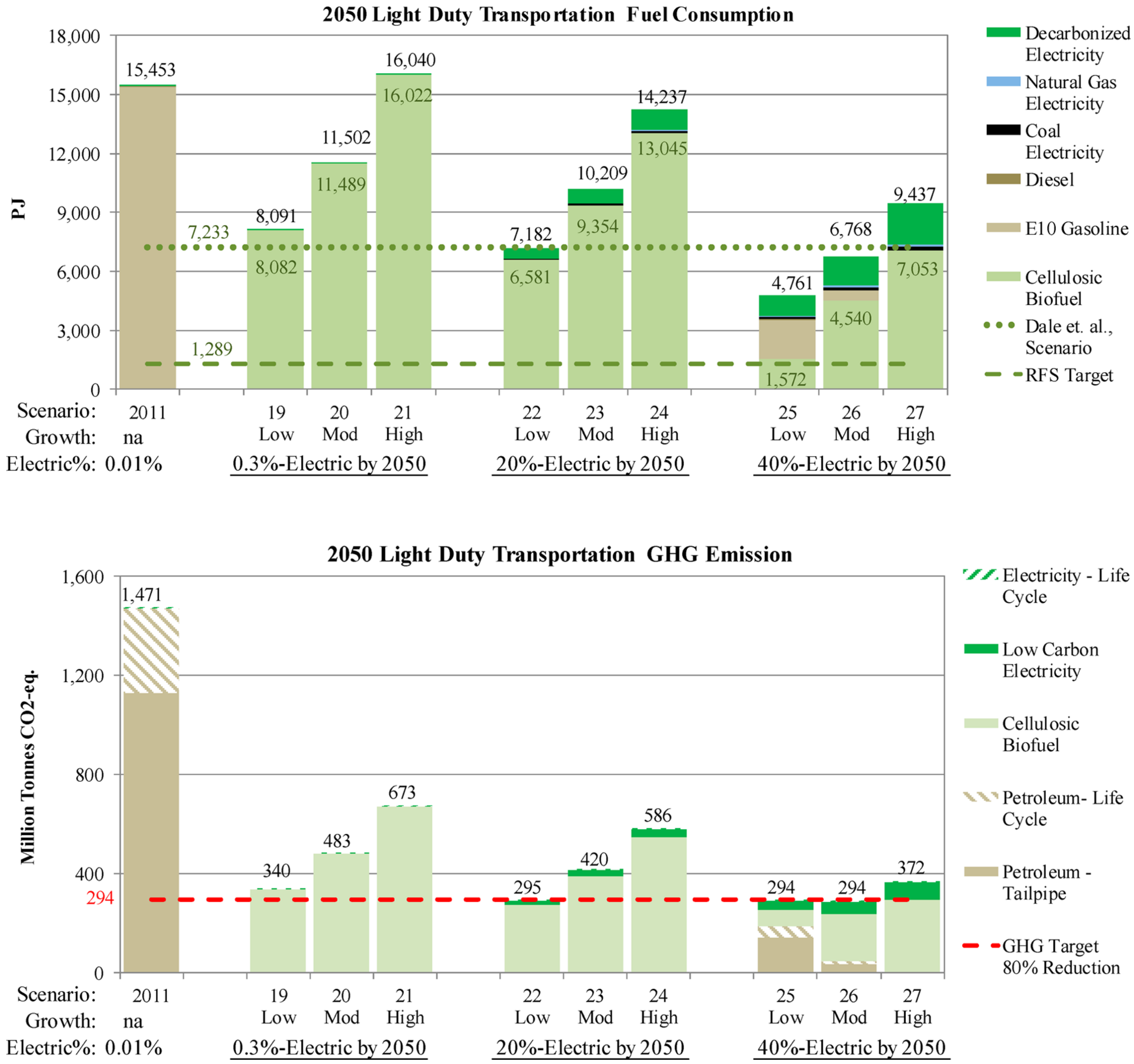


Figure 4. Nine climate-targeted scenarios, hypothetically substituting cellulosic biofuel for gasoline until GHG is reduced to 80% of 2011 levels and assuming an 80% reduction in electricity GHG intensity.

Figure 2 bottom. In scenario 3, total petroleum demand and greenhouse gas emissions are higher than the 2011 baseline. These net increases are consistent with the results of the ANL study, for the case of low electrification and high travel growth. When comparing scenario 3 to scenario 1, the high-sensitivity to growth-rate is apparent, with fuel requirements under high-growth two times (203%) higher than under low growth (e.g., no growth). The impact of technology advancement is visible comparing the 2011 baseline to scenarios 1, 4, and 7. These low-growth scenarios assume no change in travel demand between 2011 and 2050. Therefore, the associated fuel and GHG reductions are entirely attributable to advancements in vehicle fuel efficiency. In these scenarios, total vehicle fuel (petroleum and electricity) is reduced by between 48% and 69%, while GHG emissions are reduced by between 48% and 64%. As electric drives are more fuel efficient than internal combustion engines, we see that total energy requirements decrease with increasing electrification. Comparing moderate growth cases, petroleum is reduced by 19% at 20% electrification (scenario 5 versus 2) and reduced 56% at 40% electrification (scenario 8 versus 2). We account for energy use at the vehicle and not primary energy input to power plants.

Petroleum-Targeted Scenarios. Figure 3 shows the results of the petroleum-targeted scenarios. As in the reference cases, we satisfy the same travel demands with the same vehicle mixes. However, we substitute a hypothetical RFS-compliant advanced biofuel (i.e., advanced cellulosic biofuel) for gasoline on an energy basis, if needed, until we exactly meet the petroleum reduction target (i.e., to the point where gasoline and diesel consumption is reduced to 50% of 2011 levels). Therefore, we see that petroleum requirements for all scenarios (10−18) exactly meet, or are otherwise below, the 50% reduction target. None of the 40%-electrified cases (scenarios 16−18) required any contributions from cellulosic biofuel, as the electrification alone provided sufficient petroleum displacement. Scenario 13 also required no cellulosic biofuel under low growth and 20%-electrified conditions. The remaining five scenarios (10, 11, 12, 14, and 15) required widely varying contributions of cellulosic biofuel, from 316 to 8638 PJ. For comparison, we estimate the RFS goal for cellulosic fuels to be equivalent to 1289 PJ. We assume that electricity supply is 40%

DOI: 10.1021/acs.est.5b01691
Environ. Sci. Technol. 2015, 49, 8277−8286

decarbonized in the petroleum-targeted scenarios. In Figure 3 bottom, we see the resulting GHG emissions. Comparing Figure 2 to Figure 3, we see that the addition of low GHG-intensity cellulosic biofuel (assumed 60% lower than gasoline), combined with lower emission electricity, reduces GHG emissions by between 2% (scenario 10 versus 1) and 30% (scenario 12 versus 3). Still, none of the petroleum-targeted scenarios are close to satisfying the 294 million tonne (MT) GHG target.

Climate-Targeted Scenarios. Figure 4 shows the results of the climate-targeted scenarios. Scenarios 19–27 include cellulosic biofuel substitution to reduce GHG from light duty transportation to 20% of the reference GHG. We also assume that electricity is largely "decarbonized", reducing GHG intensity by 80%. At Figure 4 bottom, we see that no scenarios achieve the 80% GHG reduction without contributions from RFS-compliant advanced cellulosic biofuel. Further, only three scenarios meet the GHG target of 294 MT. The remaining six scenarios exceed the target even while replacing all petroleum with low GHG cellulosic biofuel (at 60% lower GHG intensity). Scenarios 19 and 27 are the closest to achieving the emissions target, needing and additional 15% and 29%, respectively to meet it. With much higher contributions from cellulosic biofuel, GHG emissions across all scenarios are much lower in Figure 4 than with lower cellulosic biofuel contributions in Figure 3.

At the top of Figure 4 it may be seen that Scenarios 25 and 26 (which meet the GHG target) use only 13% and 3% of the petroleum used in 2011, respectively. Only scenarios meeting the GHG target include petroleum contributions, because if they did not meet the target, additional cellulosic biofuel would be substituted for petroleum. Figure 4 also shows the hypothetical cellulosic biofuel contributions relative to the 16 billion gallons per year RFS goal (equivalent to 1289 PJ) and relative to a 400 billion liter high-production scenario recently published by Dale et al.[39] For establishing our high-production benchmark, we assumed 85% of this biofuel estimate is cellulosic (equivalent to 7233 PJ or 90 billion gallons per year). No scenarios are below the RFS goal, and only Scenario 25 (low growth and 40% electrification) is even close to it, with biofuel requirements of 1508 PJ being 17% higher. Of the five lowest GHG scenarios, four had cellulosic contributions below the high-production benchmark established by Dale et al.[36] (scenarios 22, 25, 26, 27) and one (scenario 19) was 11% higher. The remaining four scenarios exceeded the high-production benchmark by between 11–126%.

An additional sensitivity analysis was performed to extend the assessment in Figure 4 to over 135 cases, with the output the amount of cellulosic biofuel volumes required to meet GHG targets, with our assumptions (Figure S3, Supporting Information). These cases span 5-levels of electrification, 3-levels of demand growth, 3-rates of technology advancement, and 3-levels of economy-wide carbon intensity. Electrification scenarios correspond to the ANL Study (PHEV & ethanol scenario), EPRI/NRDC Study (low, medium, high scenarios), and one additional 20% electrification scenario. For each of these scenarios, three results are shown assuming high, moderate, and low rates of technology advancement, where high tech advancement corresponds to the lowest biofuel volume and vice versa. The low carbon economy assumes electricity is decarbonized by 80% and petroleum has 15% lower GHG intensity than current levels. The moderate carbon economy assumes electricity is decarbonized by 40% and petroleum has the same GHG intensity as current levels. The high carbon economy assumes electricity has the same GHG intensity as current levels and petroleum has 15% higher GHG intensity than current levels. Near misses (within 5%) are included as meeting the GHG target.

Environmental and Resource Implications. This analysis demonstrates that dramatic reductions in petroleum demand are achievable through vehicle technology improvements. Assuming travel demand grows at historic rates, vehicle efficiency alone reduces petroleum consumption significantly, but the reduction only exceeds 50% with a very high reliance on electrified vehicles. Holding VMT constant (no VMT growth), coupled with vehicle efficiency improvements, results in extensive fuel reductions: roughly halving petroleum use with almost no reliance on electricity. The assumed rates of vehicle efficiency improvement and consumer adoption should not be taken for granted, but rather would represent impressive achievements. Even in the low (0.3%) electricity cases, 38% of vehicles are powered by hybrid-electric technology by 2050. In the high (40%) electricity cases, nearly every light duty vehicle is assumed hybrid or plug-in hybrid. It is difficult to imagine achieving this level of fleet efficiency without newly invigorated public concern, cooperating vehicle manufacturers, and supportive policy.

Significant contributions from both cellulosic biofuel and electricity were necessary to meet an 80% greenhouse gas (GHG) reduction target across our range of scenarios. Scenarios relying almost exclusively on cellulosic biofuel (19–21) for light duty transport exceeded the GHG target by 15% with constant VMT (no growth) and by 134% under high-growth conditions. The scenarios with the highest rates of electrification (scenarios 25–27) were still not able to meet the GHG target, except with very large contributions from cellulosic biofuels. Cellulosic biofuels contributions exceeded the 16 billion gallons (1289 PJ) RFS goal for 2022 in all cases. The lowest cellulosic biofuel contribution was 17% higher than the RFS goal in the case of 40% electrification and no VMT growth (scenario 25). The RFS goal, however, is not a technical limitation. Five of the nine scenarios met, or nearly met, the GHG target with cellulosic biofuel requirements below, or close to, published estimates for technically achievable biofuel production.[38] With 40% electrification, the low growth and moderate growth cases met the GHG target with cellulosic biofuel contributions of 1508 PJ (18.7 billion gallon) and 4540 PJ (56.4 billion gallon), respectively, well below the 7233 PJ (90 billion gallon) benchmark.

Importantly, we are considering only fuel demands for light duty transportation, that is, cars, vans, SUVs, and light trucks. A significant level of electrification is certainly viable for these vehicles, as BEVs and PHEVs are currently commercially available. Light duty vehicles are responsible for slightly more than half of the U.S. petroleum used in the transportation sector.[27,39] The remainder of transportation petroleum, however, is used for on-road and off-road heavy duty vehicles, trains, planes, and marine vessels. Electricity is not feasible for powering planes, marine vessels, heavy trucks, and most off-road mobile work platforms though some electrification of rail transport is possible. Therefore, achieving comparable GHG targets across these transportation modes would presumably require even higher reliance on cellulosic biofuel, in addition to the volumes required for light duty transportation.

Policy Implications. Regardless of the precise consumer preferences between hybrid, plug-in hybrid, or battery electric

DOI: 10.1021/acs.est.5b01691
Environ. Sci. Technol. 2015, 49, 8277–8286

vehicles, what is germane to our conclusions is the total reliance on electricity for light-duty transportation. Our high-electrification scenarios (40% of miles) corresponded to 26% of light duty transport energy being supplied by electricity. At this level, both decarbonized electricity and substantial volumes of low-carbon liquid fuels (e.g., advanced RFS-compliant cellulosic biofuels) would be required to meet an 80% GHG reduction target. The implications of this research are daunting with regard to climate policy. Successfully decarbonizing light duty transportation requires simultaneous "successes" around several key challenges. First, growth in light duty vehicle travel would need to be moderate at most, but preferably low. Historic growth can be maintained and achieve an 80% GHG reduction only if nearly all petroleum is replaced with alternative low-carbon fuels. Second, an extremely high rate of electrified vehicle technology adoption would need to be achieved, such that nearly all light duty vehicles would need to be hybrid or electrified by 2050 and coupled to ongoing improvements in vehicle efficiency. Third, U.S. electricity supply cannot resemble the current fuel mix, but would have to be massively decarbonized; displacing the vast majority of fossil-fuel derived electricity with nuclear and renewable resources. Changes of this magnitude to transportation demand, vehicle fleet, and electricity are necessary, but still insufficient to meet an 80% GHG reduction, without additional low-carbon gasoline replacement such as that provided by cellulosic biofuels.

Over the course of 35 years, the fuel-mix powering light duty transportation could be radically different than today's, requiring only a small fraction (0−13%) of current petroleum consumption. Simultaneously achieving the petroleum and GHG reduction targets would require a monumental effort to commercialize cellulosic biofuels, as well as impressive achievements spanning transportation planning, vehicle manufacturing, electric power supply, and public policy. Still, it is technically achievable. Our assumed vehicle efficiencies were based on average (not high) rates of technology improvement. Renewable and nuclear electricity supply technologies are available today. Though continued research and development is needed, the necessary biofuel contributions are within the range of recent estimates of achievable potential.

■ ASSOCIATED CONTENT

Supporting Information

Additional details on the United States fleet modeling and fuel requirements. The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.est.5b01691.

■ AUTHOR INFORMATION

Corresponding Author

*E-mail: trunge@wisc.edu. Phone: 1-608-890-3143.

Author Contributions

The manuscript was written through contributions of all authors. All authors have given approval to the final version of the manuscript.

Notes

The authors declare no competing financial interest.

■ ACKNOWLEDGMENTS

This work was funded by DOE Great Lakes Bioenergy Research Center (www.greatlakesbioenergy.org) supported by the U.S. Department of Energy, Office of Science, Office of Biological and Environmental Research, through Cooperative Agreement DEFC02-07ER64494. Support was also provided by the Wisconsin Energy Institute at the University of Wisconsin-Madison.

■ REFERENCES

(1) Richard Nixon Address to the Nation about Policies To Deal With the Energy Shortages. November 7, 1973. The American Presidency Project. http://www.presidency.ucsb.edu/ws/?pid=4034 (accessed January 2014).

(2) U.S. Department of Energy, Energy Information Administration. U.S. Imports of Crude Oil. http://www.eia.gov/dnav/pet/hist/LeafHandler.ashx?n=PET&s=MCRIMUS1&f=A (accessed January 2014).

(3) Gupta, S. Tirpak, A. Chapter 13 Policies, Instruments and Co-operative Arrangements. IPCC Fourth Assessment Report: Climate Change 2007 (AR4). http://www.ipcc.ch/pdf/assessment-report/ar4/wg3/ar4-wg3-chapter13.pdf (accessed January 2014).

(4) U.S. Department of Energy. Barack Obama and Joe Biden: New Energy for America. http://energy.gov/sites/prod/files/edg/media/Obama_New_Energy_0804.pdf (accessed September 2014).

(5) U.S. Department of Transportation. National Transportation Statistics. Table 1-36: Roadway Vehicle-Miles Traveled (VMT) and VMT per Lane-Mile by Functional Class. http://www.rita.dot.gov/bts/sites/rita.dot.gov.bts/files/publications/national_transportation_statistics/index.html (accessed September 2014).

(6) 2017 and Later Model Year Light-Duty Vehicle Greenhouse Gas Emissions and Corporate Average Fuel Economy Standards. *Fed. Regist.*, **2011**, *76*, No. 231.

(7) Winkler, S. L.; Wallington, T. J.; Maas, H.; Heinz, H. Light-Duty Vehicle CO_2 Targets Consistent with 450 ppm CO_2 Stabilization. *Environ. Sci. Technol.* **2014**, *48* (11), 6453−6460.

(8) Meier, P. J.; Holloway, T.; Luedke, M.; Frost, E.; Scotty, E.; Williams, S.; Bickford, E. Does Natural Gas Make Sense for Freight? Environmental Implications of the "Pickens Plan". National Center for Freight & Infrastructure Research & Education, CFIRE 04-22. http://www.wistrans.org/cfire/research/projects/04-22 (accessed September 2014).

(9) Schnepf, R.; Yacobucci, B. *Renewable Fuel Standard: Overview and Issues*, Congressional Research Service Report for Congress R40155; Congressional Research Service: Washington, DC, 2013; https://www.fas.org/sgp/crs/misc/R40155.pdf.

(10) U.S. Environmental Protection Agency. EPA Proposes 2013 Renewable Fuel Standards. http://www.epa.gov/otaq/fuels/renewablefuels/documents/420f13007.pdf (accessed September 2014).

(11) U.S. Energy Information Administration. Monthly Energy Review. Table 10.1: Renewable Energy Production and Consumption by Source. http://www.eia.gov/totalenergy/data/monthly/pdf/sec10_3.pdf (accessed September 2014).

(12) Aguirre, K.; Eisenhardt, L.; Lim, C.; Nelson, B.; Norring, A.; Slowik, P.; Tu, N. Lifecycle Analysis Comparison of a Battery Electric Vehicle and a Conventional Gasoline Vehicle, 2012. http://www.environment.ucla.edu/media_IOE/files/BatteryElectricVehicleLCA2012-rh-ptd.pdf (accessed December 2013).

(13) Dincer, I.; Rosen, M.; Zamfirescu, C. Economic and Environmental Comparison of Conventional and Alternative Vehicle Options. In *Electric and Hybrid Vehicles*; Pistoia, G., Ed.; Elsevier: Amsterdam, 2010; Chapter 1, pp 1−17.

(14) Elgowainy, A.; Burnham, A.; Wang, M.; Molburg, J.; Rousseau, A. *Well-to-Wheels Energy Use and Greenhouse Gas Emissions. Analysis of Plug-in Hybrid Electric Vehicles*, Technical Report ANL/ESD/09-2; U.S. Department of Energy: Washington, D.C., 2009.

(15) Gao, L.; Winfield, Z. Life Cycle Assessment of Environmental and Economic Impacts of Advanced Vehicles. *Energies* **2012**, *5* (3), 605−620.

DOI: 10.1021/acs.est.5b01691
Environ. Sci. Technol. 2015, 49, 8277−8286

(16) Green, R.; Wang, L.; Alam, M. The Impact of Plug-in Hybrid Electric Vehicles on Distribution Networks: A Review and Outlook. *Renewable Sustainable Energy Rev.* **2011**, *15*, 544−553.
(17) Hussain, M.; Dincer, I. Life Cycle Assessment of Hydrogen Fuel Cell and Gasoline Vehicles. In *Electric and Hybrid Vehicles*; Pistoia, G., Ed.; Elsevier: Amsterdam, 2010; Chapter 11, pp 193−210.
(18) Michalek, J.; Chester, M.; Jaramillo, P.; Samaras, C.; Shiau, C.; Lave, L. Valuation of plug-in vehicle life-cycle air emissions and oil displacement benefits. *Proc. Natl. Acad. Sci. U.S.A.* **2011**, *108*, 16554−16558.
(19) Offer, G.; Howey, D.; Contestabile, M.; Clague, R.; Brandon, N. Comparative Analysis of Battery Electric, Hydrogen Fuel Cell and Hybrid Vehicles in a Future Sustainable Road Transport System. *Energy Policy* **2010**, *38*, 24−29.
(20) Schewel, L.; Kammen, D. Smart Transportation: Synergizing Electrified Vehicles and Mobile Information Systems. *Environment Magazine*. http://www.environmentmagazine.org/Archives/Back%20Issues/September-October%202010/smart-transportation-full.html (accessed December 2013).
(21) Silva, C.; Farias, T. Evaluation of Energy Consumption, Emissions, and Costs of Plug-in Hybrid Vehicles. In *Electric and Hybrid Vehicles*; Pistoia, G., Ed.; Elsevier: Amsterdam, 2010; Chapter 7, pp 193−210.
(22) Xie, Y.; Chowdhury, M.; Bhavsar, P.; Zhou, Y. An Integrated Modeling Approach for Facilitating Emission Estimations of Alternative Fueled Vehicles. *Transp. Res., Part D* **2012**, *17* (1), 15−20.
(23) Lipman, T.; Delucci, M. Expected Greenhouse Gas Emission Reductions by Battery, Fuel Cell, and Plug-In Hybrid Electric Vehicles. Electric and Hybrid Vehicles. In *Electric and Hybrid Vehicles*; Ed., Pistoia, G.; Elsevier: Amsterdam, 2010; Chapter 5, pp 113−158.
(24) Electric Power Research Institute; National Resources Defense Council; Charles Clark Group Environmental Assessment of Plug-In Hybrid Electric Vehicles. *Nationwide Greenhouse Gas Emissions*, Vol. *1*, ERPI Research Report 1015325; U.S. Department of Energy: Washington, DC, 2007. http://energy.gov/oe/downloads/environmental-assessment-plug-hybrid-electric-vehicles-volume-1-nationwide-greenhouse (accessed October 2013).
(25) Plotkin, S.; Singh, M.; Patterson, P.; Ward, J.; Wood, F.; Woof, F.; Kydes, N.; Holte, J.; Moore, J.; Miller, G.; Das, S.; Greene, D.; Rousseau, A.; Sharer, P.; Pagerit, S. *Multi-Path Transportation Futures Study: Vehicle Characterization and Scenario Analyses*, Argonne National Laboratory Report ANL/ESD/09-5; U.S. Department of Energy: Washington, D.C., 2009.
(26) Ward, J. U.S. Department of Energy, Personal Communication, March 16, 2015.
(27) U.S. Department of Transportation Federal Highway Administration. State Transportation Statistics 2010, Table VM-1: Vehicle Miles of Travel and Related Data, by Highway Category and Vehicle Type. https://www.fhwa.dot.gov/policyinformation/statistics/2010/ (accessed February 2014).
(28) U.S. Department of Transportation Federal Highway Administration. State Transportation Statistics 2010, Table MV-1: State Motor-Vehicle Registrations. https://www.fhwa.dot.gov/policyinformation/statistics/2010/ (accessed February 2014).
(29) U.S. Department of Transportation, National Highway Traffic Safety Administration. *Vehicle Survivability and Travel Mileage Schedules*, Technical Report DOT HS 809 952; NHTSA: Washington, DC, 2006.
(30) U.S. Department of Transportation, Bureau of Transportation Statistics Table 4−23: Average Fuel Efficiency of U.S. Light Duty Vehicles, 2013. http://www.rita.dot.gov/bts/sites/rita.dot.gov.bts/files/publications/national_transportation_statistics/html/table_04_23.html (accessed February 2014).
(31) U.S. Department of Transportation. Monthly Motor Fuel Reported by States, 2010. https://www.fhwa.dot.gov/policyinformation/motorfuelhwy_trustfund.cfm (accessed February 2014).
(32) Wang M. *The Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) Model*; Center for Transportation Research, Energy Systems Division, Argonne National Laboratory/Department of Energy: Argonne, IL, 2009; http://greet.es.anl.gov/ (accessed January 2014).
(33) Intergovernmental Panel on Climate Change, Working Group I. Contribution to the IPCC Fifth Assessment Report (AR5), Climate Change 2013: The Physical Science Basis. http://www.climatechange2013.org/images/uploads/WGIAR5_WGI-12Doc2b_FinalDraft_All.pdf (accessed October, 2014).
(34) U.S. Federal Register. 2014:40 CFR Part 80: EPA-HQ-OAR-2014-0575. http://www.gpo.gov/fdsys/pkg/FR-2014-08-08/pdf/2014-18568.pdf (accessed February 2015).
(35) U.S. Environmental Protection Agency. Emissions & Generation Resource Integrated Database (eGRID2012 Version 1.0). http://www.epa.gov/cleanenergy/energy-resources/egrid/index.html (accessed January 2014).
(36) Kaufman, A. S.; Meier, P. J.; Sinistore, J. C.; Reinemann, D. J. Implications of LCA Accounting Methods in a Corn and Corn Stover to Ethanol System. *Energy Policy* **2010**, *38*, 5229−5241.
(37) Kang, J. E.; Recker, W. W. An Activity-Based Assessment of the Potential Impacts of Plug-in Hybrid Electric Vehicles on Energy and Emissions Using 1-Day Travel Data. *Transp. Res., Part D* **2009**, *8*, 541−566.
(38) U.S. Environmental Protection Agency. Clean Air Markets. http://camddataandmaps.epa.gov/gdm/index.cfm?fuseaction=emissions.wizard (accessed August 2014).
(39) Dale, B. E.; Bals, B. D.; Kim, S.; Eranki, P. Biofuels Done Right: Land Efficiency Animal Feeds Enable Large Environmental and Energy Benefits. *Environ. Sci. Technol.* **2010**, *44*, 8385−8389.

DOI: 10.1021/acs.est.5b01691
Environ. Sci. Technol. 2015, 49, 8277−8286