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# **Title**: Achieving deep cuts in the carbon intensity of US automobile transportation by 2050: Complementary roles for electricity and biofuels

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## Abstract

Passenger cars in the United States (US) rely primarily on petroleum-derived fuels and contribute the majority of US transportation-related greenhouse gas (GHG) emissions. Electricity and biofuels are two promising alternatives for reducing both the carbon intensity of automotive transportation and US reliance on imported oil. However, as standalone solutions, the biofuels option is limited by land availability and the electricity option is limited by market adoption rates and technical challenges. This paper explores potential GHG emissions reductions attainable in the US through 2050 with a county-level scenario analysis that combines ambitious plug-in hybrid electric vehicle (PHEV) adoption rates with scale-up of cellulosic ethanol production. With PHEVs achieving a 58% share of the passenger car fleet by 2050, phasing out most corn ethanol and limiting cellulosic ethanol feedstocks to sustainably produced crop residues and dedicated crops, we project that the US could supply the liquid fuels needed for the automobile fleet with an average blend of 80% ethanol (by volume) and 20% gasoline. If electricity for PHEV charging could be supplied by a combination of renewables and natural-gas combined-cycle power plants, the carbon intensity of automotive transport would be 79 g $CO_2$e per vehicle-kilometer traveled, a 71% reduction relative to 2013.

## Introduction

Deep cuts to greenhouse gas (GHG) emissions from all sectors of the economy are needed to stabilize the global climate. Decarbonizing automotive transportation during the coming decades is challenging because of the need for portable, safe, and affordable energy storage in the form of batteries or an energy-dense liquid fuel. Current US passenger cars rely almost entirely on petroleum. [1] Passenger cars make up the single largest share of all transportation-related GHG emissions in the US, releasing 758 Tg/y of $CO_2$e in 2010. [2] To meet GHG emissions reduction goals will require both reductions in vehicle-kilometers traveled (VKT) and decarbonization of fuels. [3-5]

Electricity derived from low-GHG sources and biofuels are two promising options for achieving GHG intensity reductions in transportation. However, both have drawbacks that make them undesirable standalone replacements for conventional fuels. Electrification of transportation must overcome limited vehicle battery capacity, incomplete charging infrastructure, lengthy charging times, and the need for significant reductions in the carbon intensity of electricity generation.[3] Biofuels' potential scale is constrained by the availability of essential inputs: agricultural land, crop residue, and other biomass. [6] However, used together, electricity and biofuels have the potential to complement one another. Electricity could supply the majority of daily fuel demand through the use of plug-in hybrid electric vehicles (PHEVs), while biofuels could fuel long trips or travel in areas with insufficient charging infrastructure.

To explore the combined use of electricity and biofuels to substantially reduce GHG emissions from the private automobile fleet in the US, we have developed an ambitious yet achievable US county-level scenario extending to 2050 for both PHEV deployment as well as bioethanol production. County-level resolution permits an exploration of how regional differences in PHEV market adoption and driving behavior would shift electricity and liquid fuel demand. Utilizing predictions of regional PHEV market penetration, population changes, vehicle efficiency improvements, and driving patterns, we estimate how both electricity demand and liquid fuel demand for automobile transportation could evolve in the United States through 2050. We then model how biomass-derived fuel and additional electricity generation capacity could meet major components of the overall demand. We assess the resulting impact on GHG emissions and perform a sensitivity analysis around key assumptions.

## Background and Motivation

The need for a portfolio of technologies, rather than a "silver bullet," to reduce GHG emissions and fossil fuel dependence is well recognized.[4] Nevertheless, an individual technology is often assessed on the basis of whether it can alone achieve environmental goals for a particular sector. Wedge analysis has become a popular method for creating multi-technology scenarios that achieve a particular GHG reduction goal. [3,4] This approach emphasizes the end-state of societal-scale transformations, neglecting feasible market penetration rates and the extent to which different technologies interact as they scale up, either facilitating or inhibiting one another. In particular, wedge analysis is not well suited to consider the large spatial heterogeneities of feasibility, scale-up, and adoption. These nuances are particularly important in assessing passenger transportation, where consumer adoption of new vehicle technologies, availability of supporting infrastructure, and driving behavior strongly influence the potential contributions of alternative fuels, such as electricity, biofuels, compressed natural gas (CNG), and hydrogen.

Many recent studies have developed high-level scenarios aimed to achieve significant GHG emissions reductions from the transportation sector in the next 20-40 years.[3, 4, 7-13] With the exceptions of Yeh et al. [12] and Kromer et al. [9], each starts from a climate- or policy-motivated target and develops scenarios that meet the goal without grounding their assumptions in market adoption rates of vehicle technologies. None of the cited studies include US regional variation across scenarios, which could affect technology adoption rates, driving behavior, electric grid mixes, and differences in ethanol blend walls. Each of these factors could affect total energy use and GHG emissions.

As highlighted in Williams et al. [3], substantial electrification of transportation paired with carbon emissions reductions in the electricity sector is essential for achieving the 2050 climate stabilization goal of GHG emissions 80% below 1990 levels, as proposed for California. It is improbable that US automotive transportation could become fully electrified within the next four decades because of limitations in fleet turnover and the pace of battery performance improvements and cost reductions. Over that period, liquid fuels that combine gasoline with lower-carbon alternatives will provide most of the energy for private automobile transportation. Liquid biofuels, especially “drop-in” biofuels, are an attractive option because they require minimal new storage and distribution infrastructure relative to gaseous fuels, and because they can be used in spark-ignited engines with minor modifications. Biofuels are currently produced almost entirely from sugar, starch, and fats, placing them in competition with food production. [14] Significant momentum is building toward delivery of meaningful quantities of second-generation biofuels derived from lignocellulosic feedstocks. Fuels produced from lignocellulosic biomass provide an opportunity to avoid or minimize the impact on food prices by utilizing crop residues and high-yield biomass crops that can be grown on marginal land. [15]

Lignocellulosic biomass' inherent recalcitrance to chemical, biological, and physical deconstruction makes its conversion to useful fuel more challenging and costly than "first generation" feedstocks such as corn grain and cane sugar. Of the possible gasoline replacements resulting from lignocellulosic biomass conversion, ethanol appears most likely to be viable for commercial scale-up in the next few decades, although bio-based drop-in hydrocarbon fuels are drawing intense research interest and may eventually become economically attractive. [16] Ethanol is currently blended into gasoline at levels up to 10% by volume (E10). (It makes up a smaller fraction of total energy due to its lower volumetric energy content.) The US Environmental Protection Agency (EPA) recently approved the use of ethanol blends up to 15% by volume (E15) in light-duty vehicles from model years 2001 and later. [17] Ethanol-gasoline blends of up to 85% ethanol by volume (E85) can be used in flex fuel vehicles (FFV), which currently cost only $100-300 more to produce than conventional vehicles. [18] In contrast, the additional cost of a CNG/gasoline bi-fuel vehicle can be on the order of $10,000, and the cost of hydrogen fuel-cell vehicles (HFCV) plus the hydrogen distribution infrastructure is much higher. [19, 20]

## Methods

The scenario presented in this paper is based on a bottom-up approach that uses consumer adoption of PHEVs and the scale of cellulosic ethanol production as the main limiting factors in decarbonizing automotive transportation. Based on studies that address charging infrastructure development, median household income, and relevant policy mandates or incentives, we have developed a county-level PHEV adoption scenario that extends to 2050. To ensure that PHEVs can be substituted for conventional vehicles as functional equivalents, we focus our analysis on passenger cars, excluding sport-utility vehicles (SUVs) and light trucks. Per-capita VKT, trip length, and expected fuel efficiency improvement data allow us to estimate the net change and geographic shifts in transportation-related electricity and liquid-fuel demand. To assess the likely reduction in reliance on gasoline, we estimate the quantity of Miscanthus, corn stover, and wheat straw available for conversion to fuel and compare the resulting volume of ethanol with the quantity of ethanol necessary to replace all conventional gasoline used for passenger automobiles with E85. The resulting lifecycle GHG emissions are calculated on both a fleet-total and per-VKT basis using a range of electricity mixes.

### *PHEV deployment scenario*

Our PHEV deployment scenario builds on the baseline scenario provided by the Energy Information Administration's (EIA) 2012 Annual Energy Outlook, which provides projections for new car sales and fuel economy improvements through 2035. Sales are disaggregated into nine geographic regions and fourteen vehicle types (see Supporting Information). [21] We have extended these projections to 2050 by assuming sales grow proportionally with regional population. [22] Population projections through 2050 are based on the 2010 RPA Assessment County Level Projections for Scenario A1B.[23] The 2012 EIA projections are conservative in that they tend to correspond to a "business as usual" approach that holds alternative fuel vehicles at a negligible share of total passenger car sales. In contrast, our scenario predicts a much more aggressive deployment of PHEVs. To incorporate these PHEV projections into the EIA baseline scenario, we hold total vehicle sales equal to EIA-projected values and assume that projected PHEV sales will displace what would otherwise be conventional gasoline vehicle sales. Diesel, CNG, EV, and HFCV sales projections in the EIA scenario remain unchanged.

Historical fuel economy data through 2008 are from the US Bureau of Transportation Statistics. [24] Data for new vehicles purchased between 2009 and 2012, as well as projections out to 2035, are from the 2012 EIA Annual Energy Outlook. [25] Since the EIA fuel economy projections are essentially linear in the long term, 2036-2050 estimates are based on the slope from the 2025-2035 EIA projections. We adjusted fuel economy data down by 15% to account for the shortfall between fuel economy ratings and actual efficiency achieved by typical drivers. [26]

Market adoption projections, while subject to large uncertainties, are necessary to ensure that scenarios are constrained by appropriate fleet turnover rates and typical consumer adoption patterns. Upfront cost reductions, policy incentives, fuel prices, consumer purchasing power, and infrastructure development all contribute to the speed of adoption. Logistic functions, and particularly sigmoid functions, are frequently used to simulate market adoption patterns. Sigmoid functions model three stages: slow initial adoption, more rapid growth as the technology's costs are lowered through economies of scale and learning curves, and finally slower growth as the technology approaches market saturation. PHEV market adoption curves produced by detailed agent-based models and general equilibrium models have been found to resemble sigmoid functions. [27, 28] We use a sigmoid function to estimate PHEVs' growing share of total new car sales beginning in 2013 and ending in 2050 (see Figure 1a). As applied, this function returns a fraction that, when multiplied by total sales for a given year, yields the total PHEV sales in that year. The base scenario assumes attainment of a 2050 goal of 70% sales penetration, based on results from the MIT Emissions Prediction and Policy Analysis (EPPA) general equilibrium model presented in Karplus et al. [27], which assumes that PHEVs cost 30%

more than their traditional internal combustion engine counterparts and that the US enacts legislation aimed at stabilizing atmospheric $CO_2$ at 450 ppm. These fleet penetration results are slightly below the “Medium” PHEV adoption scenario presented by the Electric Power Research Institute (EPRI) [29]. Figure 1a depicts our basic assumptions about the battery ranges of vehicles sold in each year, beginning with a roughly equal split between 16 km (10 mi) and 64 km (40 mi) ranges in 2013 and gradually transitioning to a split between 97 km (60 mi) and 161 km (100 mi) ranges in 2050. Details are provided in the Supporting Information.

In addition to its temporal dimension, PHEV market adoption will vary regionally. Previous research has indicated that income, commitment to environmentalism, high occupancy vehicle (HOV) lane incentives, and gasoline prices impact HEV adoption rates. [30] PHEVs also have an infrastructure component: drivers may be more likely to purchase a PHEV if they have ready access to charging infrastructure at home and in their community. To capture these differences, the period between 2013 and 2050 is separated into five phases: (1) beginning with early adopter cities, (2) adding the top 20% of counties by median income, (3) including early adopter states, (4) expanding to the top 50% of counties by median income, and (5) finally including the entire continental United States (shown in Figure 1b). The Supporting Information contains source data for each group. Each county is capped at an 80% PHEV share of passenger vehicle sales to allow for baseline growth in sales of diesel, HFCVs, CNG cars, and other alternative fuel vehicles as defined by the EIA Annual Energy Outlook. Many later-adopting counties do not reach this 80% cap by 2050.

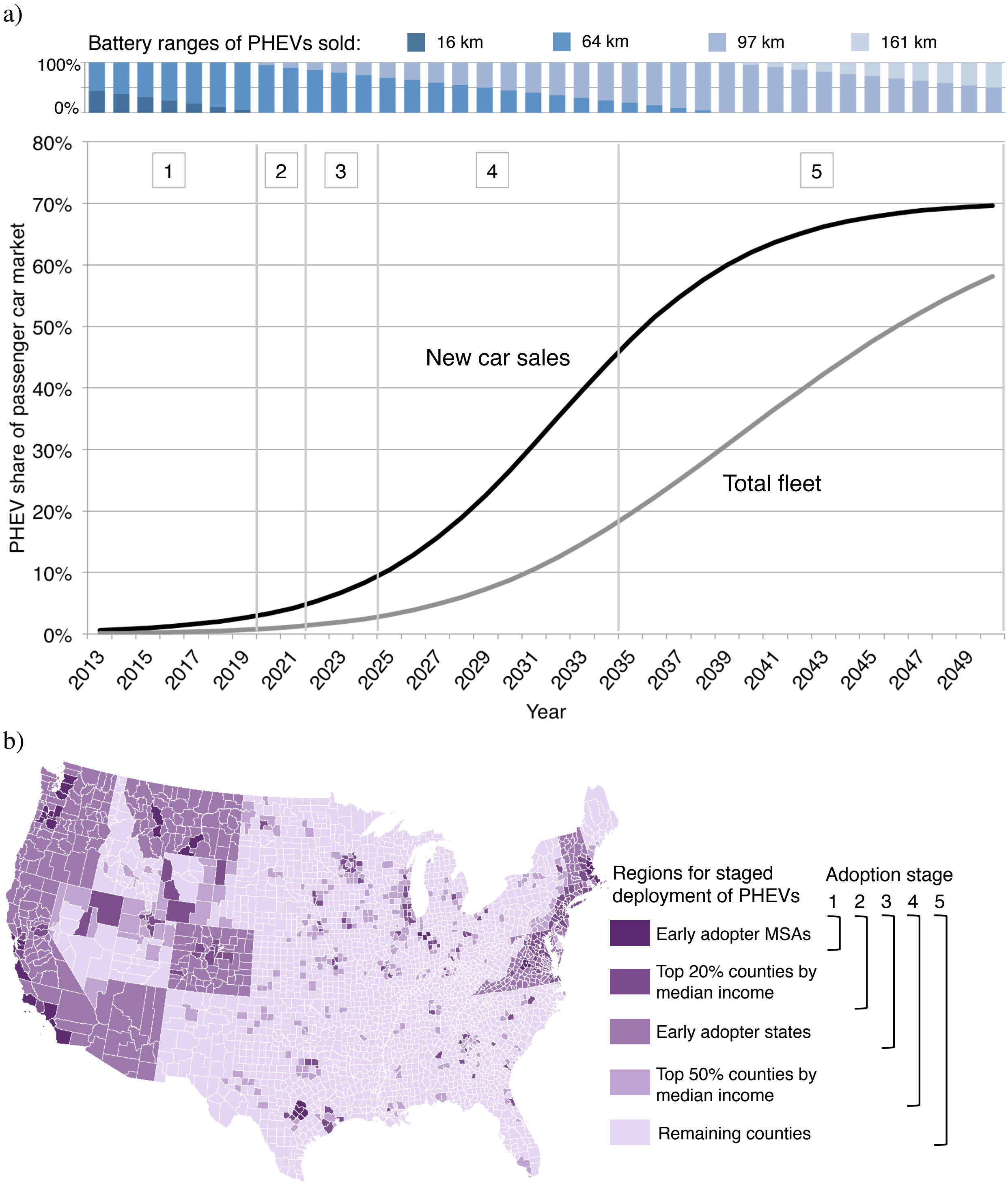

Figure 1: a) Plug-in hybrid vehicle sales curve, resulting fleet penetration, and distribution of battery ranges by sales year; b) Adoption of PHEVs by region, with numbered adoption stages corresponding to growth phases in (a)

*Driving behavior*

Driving behavior influences automotive energy use. Total VKT driven per year determines the energy required, and typical trip lengths influence the fraction of the distance driven in a PHEV that can be powered by battery. Empirically, annual VKT is not constant, but rather declines (on average) with a car's age. Equation S3 is used to model this relationship for our scenario: new cars are driven 26,000 km (16,000 mi) in their first year and shorter distances in each subsequent year. More detail is provided in the Supporting Information. Nationwide VKT by light-duty motor vehicles increased by 34% between 1990 and 2010.[2] Future changes will depend on population growth, patterns in urban development, fuel prices, and general economic conditions. Our calculations project a 65% increase in total fleet VKT per year between 2013 and 2050. This result is partially attributable to a 34% projected increase in total US population.[23] The remaining change reflects a projected increase in annual per-capita VKT of 23%. For comparison, the CA-TIMES model incorporates an expected 37% increase in per-capita VKT in California between 2010 and 2050.[31]

Transportation infrastructure in a given region influences residents' driving behavior. We use the 2009 National Household Transportation Survey trip-length data to develop county-level estimates of the fraction of total daily VKT that can be driven in all-electric mode for batteries ranging from 16- to 161-km ranges. Drivers are assumed to start the day with a full charge and operate their PHEVs in charge-depleting mode, switching to charge-sustaining mode once the battery is depleted. The assumption that vehicles are only charged once per day could result in an underestimate of the distance driven in all-electric mode if, for example, drivers are able to charge at both home and work. Weighted by population, the national averages of VKT powered by electricity for 16-km, 32-km, 48-km, 64-km, 97-km, and 161-km ranges are 24%, 42%, 54%, 63%, 76%, and 93%, respectively (see Supporting Information). We assume that liquid fuels provide the remaining energy.

*Cellulosic ethanol production scenario*

The total quantity of biomass that can be feasibly utilized for fuel production and the issue of whether current corn ethanol should be part of a future biofuel mix are both hotly debated topics. We assume that corn ethanol production will be held constant at current levels until the blend wall becomes a limiting factor, at which point corn ethanol will be phased out in favor of cellulosic ethanol. We assume that cellulosic ethanol will be produced from a combination of corn stover, wheat straw, and dedicated Miscanthus crops. Corn stover and wheat straw comprise the majority of herbaceous crop residue in the US. Miscanthus is considered one of the most promising options as a high-yield, low-input (fertilizers, biocides, irrigation water), dedicated biomass crop. [15, 32] Potential biomass sources are screened based on their access to transportation infrastructure and proximity to enough other biomass to justify a commercial-scale biorefinery. This approach provides a spatially explicit mapping of how cellulosic ethanol production can be scaled up to satisfy liquid fuel demands in a partially electrified passenger transportation system.

Miscanthus availability is based on a land conversion scenario presented in Scown et al. [6] that prioritizes conversion of Conservation Reserve Program (CRP) land, followed by the lowest-value cropland available within the appropriate growing region, excluding drought-prone regions. This Miscanthus scenario achieves a target ethanol production of 40 billion liters per year. Corn stover and wheat straw availability are based on estimates from the US DOE *Billion-Ton Update* report, which accounts for regional variations in sustainable crop residue removal rates and temporal changes in these rates as farming practices evolve. [32] Perlack and Stokes [32] project increases in biomass availability by farm gate price through 2030. We assume that any biomass priced below $60/metric ton is available for conversion, which is equal to the break-even cost of producing Miscanthus when the opportunity cost of farmland is included. [33] Because there is likely to be a lag between biomass availability increases and resulting increases in biorefining capacity, we consider biomass availability in 2030 to be a reasonable predictor of biorefining capacity in 2050. Total biomass availability is presented in Figure S2a in the Supporting Information. Biomass-producing counties without sufficient access to rail infrastructure are eliminated from the scenario (see Supporting Information).[34]

We use biomass availability to run a biorefinery site-selection analysis in ArcGIS. Candidate biorefinery locations are established at county centroids and screened based on their proximity to sufficient biomass supply and transportation infrastructure. Through location-allocation network analysis in ArcGIS, we identified 107 county centroids as optimal biorefinery locations in 2050. Between 2013 and 2050, we assume that total cellulosic ethanol production grows linearly and that all established biorefineries continue to operate through 2050. Biorefinery locations are shown in Figure S2b in the Supporting Information, along with the rail paths required to transport biomass to each one. The resulting utilization is 80% of the original 320 million metric tons (20% moisture content) available in our biomass production scenario. Biomass transportation distances are calculated based on ArcGIS closest facility network analysis, yielding a weighted average of 75 km. Because this process identifies optimal routes, closest facility analysis may underestimate true distances traveled. [35] The influence on the final results is minimal.[6, 35]

Total cellulosic ethanol production sums to 1.4 trillion MJ (60 billion liters), which travels an average of 515 km to fueling stations if all US fuel terminals are ethanol-equipped. The addition of corn ethanol, which is assumed to remain at 0.5 trillion MJ (21 billion liters) of annual consumption by passenger cars until being gradually phased out starting in 2045, brings domestic ethanol supply to 100% of projected E85 blending capacity in gasoline after accounting for geographic and seasonal variations in blend walls (see Supporting Information). Note that total US corn ethanol production is higher, totaling to 1.2 trillion MJ, but only a fraction of that is used in passenger cars. Rail paths from biorefineries to blending terminals are shown in Figure S2c and highway paths from terminals to county centroid are shown in Figure S2d in the Supporting Information.

### *Lifecycle greenhouse gas inventory*

To gauge potential GHG reductions, it is important to capture both the tailpipe and upstream GHG emissions associated with transportation fuels. In some cases, these emissions are fairly well understood, but some fuel production/use pathway emissions are subject to significant uncertainty. Gasoline and diesel lifecycle GHG footprints do not vary substantially in the literature, while biofuel and electricity GHG footprints depend on many embedded assumptions. [36, 37] For fuels whose lifecycle GHG emissions are less variable, including gasoline, diesel, corn grain ethanol, CNG, liquefied petroleum gas (LPG), and hydrogen, we rely on results from the Argonne National Laboratory GREET fuel cycle model. [38] GREET may underestimate the long-term GHG footprint of gasoline and diesel if oil becomes more energy-intensive to extract and process, which would slightly increase our GHG results.[39] Vehicle manufacturing emissions are not included in our life-cycle assessment. We note that although there can be differences in energy inputs and carbon emissions associated with the manufacturing process of different vehicles, the difference between a conventional vehicle and a PHEV, normalized over the vehicles' lifetimes, is relatively small. [40]

Data sources and assumptions for each fuel pathway are shown in Table S2. Because our scenario does not include any increase in corn grain ethanol production, and because we limit conversion of land for dedicated biomass crops to CRP and marginal land, we exclude indirect land use change (iLUC) impacts resulting from land conversion. Potential iLUC factors are included as part of the sensitivity analysis. There is significant uncertainty in direct land use change emission estimates for dedicated biomass crops based on soil type and farming practices, [6, 41] which are addressed in the sensitivity analysis as well. Even at the high end of ranges for iLUC and direct land use change effects, all of the cellulosic ethanol included in our scenario meets the GHG-intensity requirements to qualify for the US Renewable Fuel Standard mandate.

Electricity and cellulosic ethanol are the two transportation energy sources for which GHG footprints are both highly uncertain and important to determining the overall GHG-intensity of the scenario presented here. The electric grid is likely to change dramatically between now and 2050 owing to the significant number of coal-fired power plants nearing retirement, declining costs for renewable energy options, growing availability of natural gas from hydraulic fracturing, and the associated recent decrease in natural gas prices. [42, 43] The increase in electricity demand projected to occur under our scenario, in addition to baseline non-transportation-related growth, will require construction of significant new electric generating capacity. An increase in the share of electricity generated by natural gas is likely owing to increased utilization of shale gas. Depending on the fate of national carbon emissions reduction policies, expanded gas use may be accompanied by an increase in renewables such as wind and solar. To address such uncertainties, we assume that the additional electricity generated to meet the needs of charging vehicles will range from 100% natural gas-fired power plants similar to those operating today (42% efficiency) to 100% renewables. Because renewables have lifecycle GHG emissions associated with the material and construction energy inputs, we use a wind farm case study as documented by Pacca and Horvath [44] and normalized over the turbines' 20-year lifespan to estimate these emissions.

To meet transportation energy demand not satisfied by electricity, we assume that cellulosic ethanol is produced from three feedstocks: corn stover, wheat straw, and Miscanthus. For dedicated Miscanthus crops, we use the long-term "Scenario 6" presented in Scown et al. [6], where soil carbon is assumed to have reached equilibrium (or near equilibrium). For crop residues such as corn stover and wheat straw, assigning environmental impacts to coproducts is a contentious allocation issue within the lifecycle assessment community. [45] Where possible, we use system expansion, which is the preferred method in the ISO 14044 standards for performing life-cycle assessment. [46] In the case of crop residues, we assign baseline cultivation impacts to the primary food products. Additional harvesting energy use and fertilizer application required for residue recovery are allocated to the crop residues. All three feedstocks are converted to ethanol via dilute acid pretreatment, enzymatic hydrolysis, and fermentation. During this conversion process, lignin and other solids that cannot be converted to fuel can be burned onsite to produce process heat and electricity.[47]

## Results

### *Electricity and liquid fuel demand for PHEVs*

The scenario is based on historical and projected future vehicle sales, expected annual VKT by vehicle age, and vehicles' average fuel economy by model year. Results correspond to a total passenger car fuel consumption of 7.3 trillion MJ in 2013, as shown in Figure 2. In 2010, total fuel consumption by passenger cars was estimated at 260 billion liters or 8.0 trillion MJ, assuming an average mix of 10% ethanol and 90% gasoline.[1] After a period of sustained growth, automotive fuel consumption peaked in 2005 and has declined each year through 2010; this decline of 13% over 5 years is largely attributed to the economic recession and rising fuel costs. If the decline continues through 2013, we expect our estimate to be fairly consistent with real-world data.

Figure 2 shows that, despite projected population and per-capita VKT growth, gasoline demand decreases substantially. Subsequent to 2010, Figure 2 shows that our estimate of corn ethanol use remains at a constant level until the blend wall begins to limit ethanol demand in 2045, at which point corn ethanol is phased out in favor of cellulosic ethanol. Diesel experiences some growth, and gasoline use declines as alternative fuel production grows. Unlike electricity for PHEVs, flex-fuel technology adoption is not likely to be the limiting factor in cellulosic ethanol production increases. Rather, production will be limited by how fast production costs decline and the rate at which commercial-scale facilities can be sited and built. We assume that flex-fuel technology will also be implemented in PHEVs. Here, we make the assumption that growth occurs linearly, reaching maximum production as calculated in the cellulosic ethanol scenario by 2050. Despite ambitious projections for PHEV market penetration, we estimate that electricity's share of total energy demand grows slowly until 2030. Total energy demand decreases as electricity demand increases because electric motors' efficiency is much higher that of internal combustion engines. Scale-up of cellulosic ethanol is important to achieving short-term GHG emissions reductions. Although the scale of ethanol production is constrained, because of the significant contributions of electricity to total demand, this scenario reaches the maximum volume that can be absorbed by an E85-dominated market. [17] Though outside the scope of this study, additional GHG emissions reductions can be achieved if bio-based diesel substitutes are brought to market at a large scale.

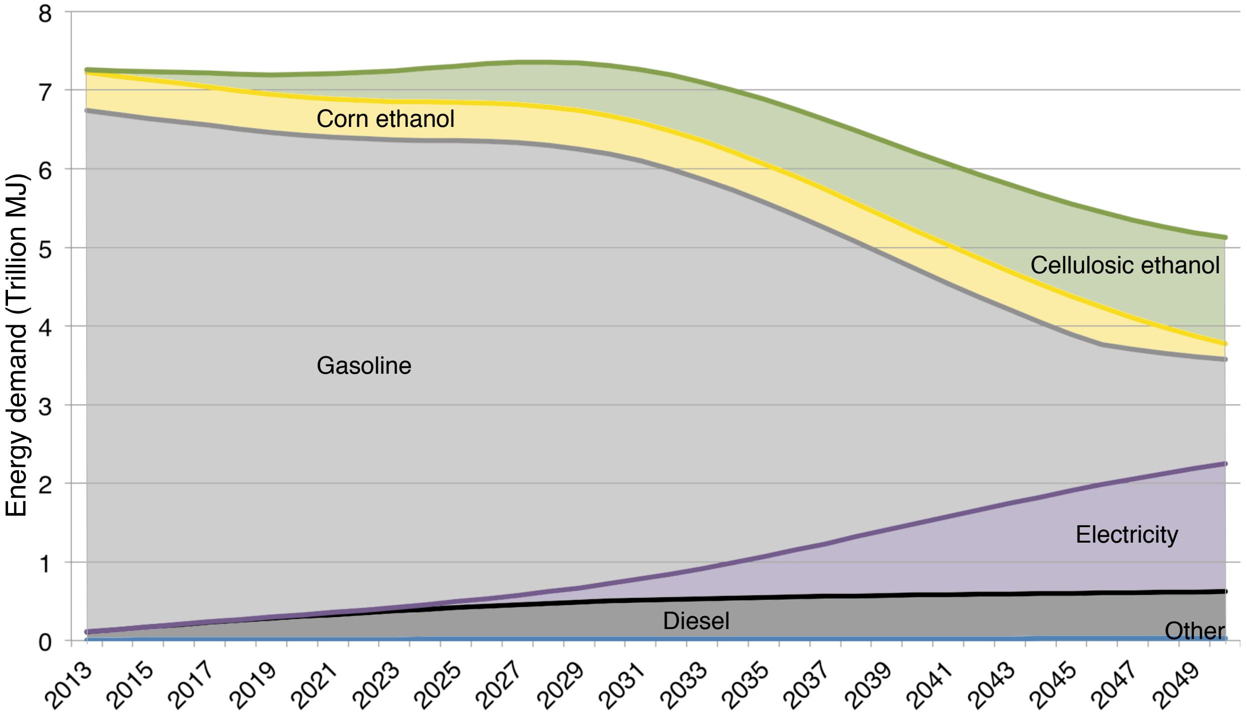

Figure 2: Projected total passenger vehicle fleet fuel demand (trillion MJ/year)

In addition to estimating the total quantities of fuels required by the passenger vehicle fleet, understanding regional changes in electricity demand offers important insight needed to assess how PHEV deployment will impact the electricity grid. Disaggregating by region provides insight into what renewable resources are available to meet this future demand. Figure S3 in the Supporting Information shows the calculated changes in 2050 electricity demand relative to 2009 demand as a result of the increased demand for electrical energy for vehicle charging. This result does not include electricity demand increases resulting from economic and population growth. The largest increases in power demand occur in the West (16%) and Northeast (17%). The western United States has significant solar, hydropower, and biomass power potential and both regions can install substantial offshore wind capacity. [48]

*Lifecycle greenhouse gas emissions*

Figure 3 presents estimated reduction in the GHG-intensity of passenger vehicles based on EIA-projected fuel economy improvements and further reduction in gasoline use in favor of cellulosic ethanol and electricity. We note that, based on the PHEV penetration and biofuel production levels included in our scenario, this reduction is roughly linear. Fleet average GHG-intensity reaches 79 g $CO_2$e/VKT by 2050, a 71% decrease from 2013 levels. The error bars reflect variability in emissions from cellulosic ethanol production and electricity generation. The average case for electricity represents a grid mix beginning as the current natural gas power plant fleet in 2013, decarbonizing linearly until 2050, at which point a mix of 50% renewables and 50% natural gas combined cycle (NGCC) power plants supplies the marginal source of electricity for vehicle charging. At the upper bound of the error bars, natural gas-fired power plants with efficiencies comparable to those operating today will supply 100% of the power for vehicle charging, and at the lower bound renewables are able to supply all the power demanded by PHEVs. For cellulosic ethanol, the lower bound represents a scenario in which Miscanthus crops planted on formerly tilled cropland are still sequestering carbon, as represented by "Short

Term Scenario 6" in Scown et al.[6] The period before degraded soils planted with Miscanthus or other carbon-sequestering plants reach carbon sink capacity is uncertain, but estimated to be on the order of 20-50 years.[49-51] As a result of the uncertainty in soil carbon fluxes and electricity sources, the 2050 carbon intensity could range from 45 to 120 g $CO_2$e/VKT. Figure S4 shows total GHG emissions for the passenger vehicle fleet between 2013 and 2050. Total fleet GHG emissions are reduced by 52%. The larger reduction in per-VKT GHG-intensity highlights the importance of efforts to reduce per-capita VKT in parallel with efforts to decarbonize transportation fuels.

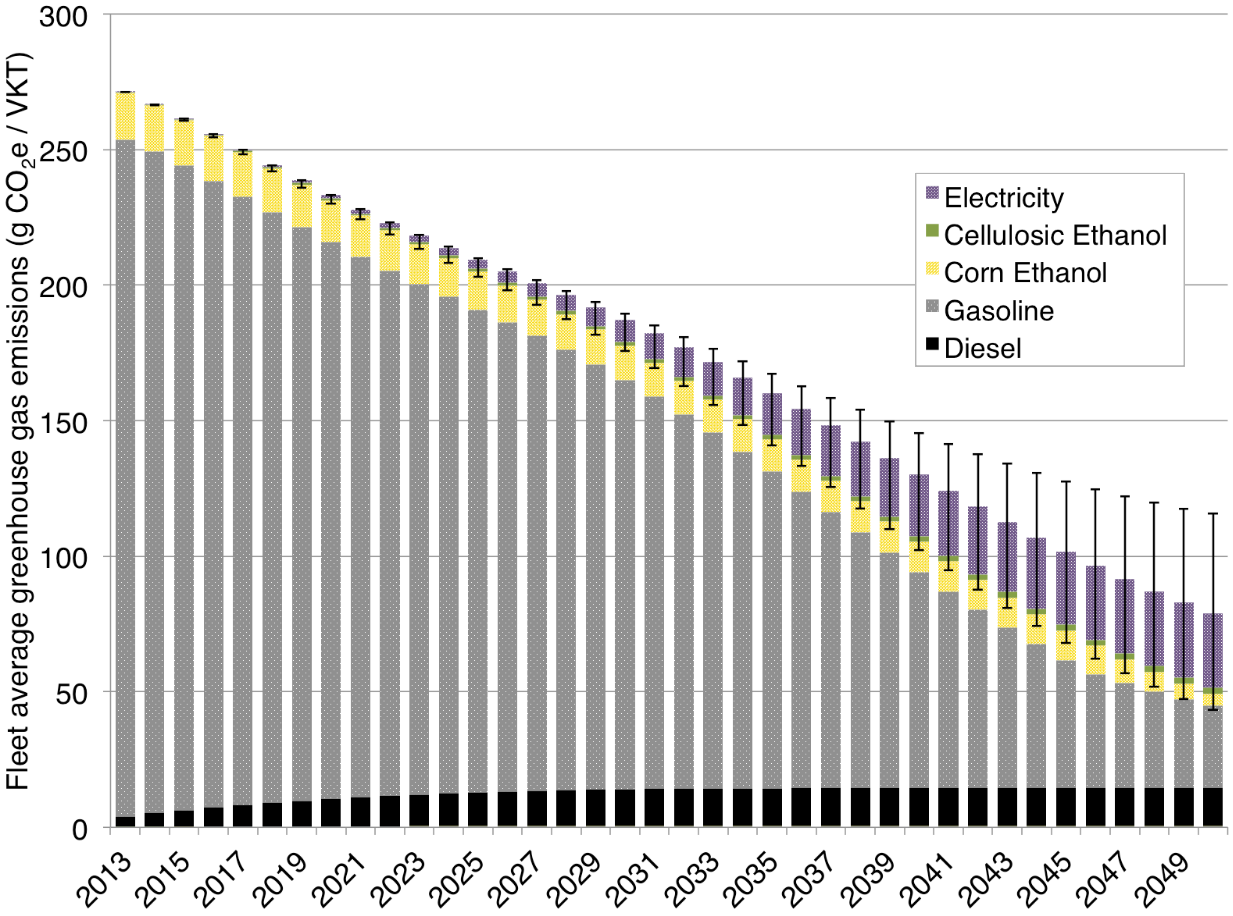

Figure 3: Passenger car fleet average greenhouse gas intensity of passenger transportation. Contributions from CNG, LPG, and hydrogen are negligible, and not visible in this chart. Error bars reflect variability in emissions from cellulosic ethanol production and electricity generation.

Table 1 explores the sensitivity of 2050 fleet-wide energy use and GHG emissions results to variations on some of the simplifying assumptions built into our analysis. A less aggressive PHEV adoption curve, where total sales penetration in each year is reduced by 20%, causes the results to differ substantially: 31% increase in primary fuel demand, 19% reduction in electricity demand, and 24% increase in GHG emissions. Slowing the flex-fuel vehicle adoption rate such that only 75% of cars are flex-fuel in 2050 has a less dramatic influence, resulting in a 5% increase in GHG emissions. Accounting for potential variation in charging patterns and trip lengths, we vary the fraction of total VKT driven on PHEV batteries of different ranges by 20%, which results in only a 2% difference in GHG emissions, but larger differences in primary fuel and electricity demand. Including iLUC factors, assuming that dedicated biomass crops are expanded at the expense of fuel crops, causes total GHG emissions to increase by 9%.

Table 1: Sensitivity analysis for selected parameters and resulting change in total fleet energy use and emissions

| Simplifying assumption | Variation | 2050 primary fuel demand | 2050 electricity demand | 2050 GHG emissions |
|---|---|---|---|---|
| Aggressive PHEV adoption curve | • 20% reduction in adoption rate for all years | +31% | -19% | +24% |
| Real-world fuel economy shortfall of 15% | • Shortfall increases to 20% due to increasing congestion | +6% | +6% | +8% |
|  | • Shortfall decreases to 10% due to improved technology | -6% | -6% | -7% |
| Battery ranges for new PHEVs sold in 2013 split between 16-km and 64-km range, increasing to a split between 97-km and 161-km range by 2050 | • 100% of new PHEVs sold with 64-mi batteries for all years after 2020 | +9% | -19% | +2% |
| Fraction of VKT per vehicle driven on the battery for each range calculated assuming once-a-day charging | • Share of VKT driven on the battery increases by 20% for all ranges | -7% | +15% | -2% |
|  | • Share of VKT driven on the battery decreases by 20% for all ranges | +9% | -19% | +2% |
| 100% flex-fuel vehicle adoption by 2050 | • 75% flex-fuel vehicle adoption by 2050 | No change | No change | +5% |
| Electricity carbon intensity in 2013 corresponds to that of existing natural gas power plants and decreases linearly, reaching 50% NGCC, 50% renewables by 2050 | • 100% of electricity supplied by natural gas power plants comparable to existing plants | No change | No change | +49% |
|  | • 100% of electricity supplied | No change | No change | -35% |

|  |  |  |  |  |
|---|---|---|---|---|
|  | by renewables |  |  |  |
| Soil carbon reached equilibrium for dedicated biomass crops | - Dedicated biomass crops still sequestering carbon to the soil | No change | No change | -10% |
| No indirect land use change (iLUC) impacts resulting from growth in dedicated biomass crops | - iLUC factor equal to CA Air Resources Board factor of 30 gCO2e / MJ applied to dedicated biomass crops | No change | No change | +9% |

## Discussion

Through a detailed analysis with high geographic resolution (county-level), we have presented and evaluated a feasible path to substantial carbon emissions reductions in the passenger-vehicle transportation sector for the US. Accounting for regional differences in population growth, market adoption rates, driving behavior, and proximity to potential biofuel production makes possible a more informed understanding of how demands on energy resources and infrastructure may shift in coming decades. This level of geospatial disaggregation also sets the stage for more robust predictions of possible human health and other highly localized impacts from different transportation energy strategies. [52, 53]

The scenario analysis presented here highlights the fact that the US vehicle fleet is more likely to achieve substantial carbon emissions reductions with a portfolio approach that includes both liquid fuel substitutes and new vehicle technologies. This result arises because the pace at which alternative vehicles can penetrate the market is limited by fleet turnover rates and the willingness of consumers to adopt an unfamiliar vehicle technology, particularly when the technology has a substantial upfront cost premium relative to conventional options. Ethanol demand is limited in the short term by the fraction of flex-fuel vehicles that can be added to the fleet, but we expect that, because of the maturity and relatively low cost of flex-fuel technology, its use in new vehicles could be expanded if manufacturers perceived a growing demand.

Analysis reveals that cellulosic ethanol can play a significant role in achieving GHG emissions reductions, even when limited to herbaceous crop residues or derived primarily from biomass crops grown on CRP and low-value cropland. When growth in cellulosic ethanol production is combined with declining production rates of ethanol from corn grain, fuel ethanol production could reach the US average flex-fuel blend wall of 80% of total gasoline/ethanol needs for passenger cars. However, cellulosic ethanol production in our scenario only meets one quarter of the 2022 mandate of 16 billion gallons established in US Renewable Fuel Standard.

Another important finding is the degree to which electricity generation will determine the magnitude of achievable GHG emissions cuts in the transportation sector. Vehicle charging profiles can change significantly depending on when drivers choose to plug their vehicles in, and that timing will determine whether PHEVs will take advantage of excess generating capacity at night or steepen daytime peak demand.[54] The load profile in turn determines the type of electricity likely to satisfy vehicle charging needs.[40] If additional power for PHEVs can be generated using only renewables, the carbon-intensity of passenger transportation could be reduced by an additional 35% in 2050 relative to 2013.

A key message conveyed by these results is that, although PHEV adoption and increased production of cellulosic ethanol can reduce the carbon intensity of passenger vehicle transportation, per-capita VKT is also important for its influence on the GHG footprint of transportation. Our analysis predicts a 23% increase in per-capita VKT and comparable studies have indicated even greater increases, although per-capita VKT must level off eventually.[31]

Mode switching and increasing vehicle occupancy through carpooling could help to stabilize or reduce per-capita VKT. Combining behavioral changes with vehicle electrification, biofuels, and electricity decarbonization will help to put an even lower-carbon passenger transportation system within reach.

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## Associated Content

A detailed description of data, sources, analytical methods, and tables with numerical results. This material is available free of charge via the Internet at http:// pubs.acs.org. Additional spreadsheets and documentation are available for download at www.cscown.com/supporting-information

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